



PHD

Locating wireless base stations within a dynamic indoor environment

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Locating wireless base stations within a dynamic indoor environment

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Electronic and Electrical Engineering

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Dedicated to my parents and my brothers

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Abstract

The mobility that wireless communication offers to users, added to the ease of installation have increased the demand on such communication systems. However, the main drawback of wireless communication is the degradation of the signal as it travels through the channel due to the different propagation mechanisms the signal undergoes. To minimise the effect of the channel and get the best service, the base stations must be appropriately located within the environment. This requires proper knowledge of the channel characteristics. Ray tracing software is used throughout this work to generate the channel characteristics of an indoor environment. After getting the channel characteristics, a novel cost function is defined based on the path loss values and it is then optimised. Once the optimal base stations' positions are found, the minimal amount of power required to cover a predefined percentage of the possible receivers' locations is calculated.

On the other hand, a receiver's position acquiring enough field strength does not necessarily enjoy the service. This depends on the time dispersion parameters values relative to the symbol rate. The time dispersion parameters have always been ignored in the literature while finding the optimal base stations' locations. Three cost functions that take into consideration both the path loss and rms delay spread, for the first time in the literature, are therefore defined. The cost functions are optimised and their corresponding results are compared.

Furthermore, indoor environments have always been considered static which is never realistic. They are subject to continuous changes such as opening doors and windows as well as the presence of people. The first detailed analysis and quantified results of the effect of a dynamic environment on the optimal base stations' positions and minimal emitted power are presented. It is shown that the optimal base stations' locations and minimal emitted power are sensitive to such environment changes. The environment changes can also disturb the service for active receivers. Three techniques to overcome the effect of environment changes and bring the disturbed service back to receivers are proposed. The first two techniques rely on increasing the emitted power or changing the antenna polarisation. The third technique is a novel technique that gives the base station the ability to automatically move in various directions within a limited distance. The techniques are tested and their efficiency and limitations are discussed.

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List of Abbreviations

BS	Base Station
FDTD	Finite Difference Time Domain
LOS	Line of Sight
N-LOS	Non-Line of Sight
RMS	Root Mean Square

Chapter 1: Introduction

Wireless communication is the transfer of information in the form of electromagnetic waves. The transmission distance can vary from few metres in the case of a Bluetooth earphone, for example, to thousands of kilometres as in the case of communication satellites. The transmission mode can be simplex, half-duplex or full-duplex [1]. A simplex system can only send information in one direction. An example of a simplex system is an infrared remote control. A half-duplex system can send and receive information on the same channel but not at the same time. Bluetooth data transfer between two laptops is an example of a half-duplex system where the user can either transmit or receive data at a given time. WiFi 5 (IEEE 802.11a), WiFi (IEEE 802.11b), IEEE 802.11g and IEEE 802.11n are other examples of half-duplex systems. On the other hand, a full-duplex system can send and receive information at the same time over two separate channels.

Wireless systems are classified based on the area they cover into megacell, macrocell, microcell, picocell and femtocell. Smaller cells are used to increase the network capacity within areas with high users' density. Picocells and femtocells are used in small indoor environments which are the target of this research.

Due to the presence of obstructions between the transmitter and the receiver, the signal can be reflected, refracted, diffracted or scattered. Thus, the signal will arrive at the receiver from multiple paths having random amplitude, phase shift and time delay. These multipaths can add constructively or destructively so that the signal may be unintelligible at the receiver. The effect of multipaths is modelled as path loss, shadowing or slow fading, and fast fading or multipath fading. In addition, the signal is also susceptible to additive noise such as thermal noise, shot noise, interference due to other transmitters and electrical equipment [2].

The flexibility that wireless communication systems provide in terms of installation and users' mobility has contributed to the widespread use of wireless systems especially indoor systems. However, the main drawback of wireless communication is the distortion of the signal as it travels through the channel due to the different propagation mechanisms. Coverage should be provided at all locations in the environment so that the user can move freely within the environment without losing the

connection. In addition, the bit error rate, latency and jitter must be kept negligible while keeping a high throughput. Therefore proper knowledge of the channel characteristics is necessary to select the appropriate number of base stations, adjust their positions and the amount of power that should be radiated in order to overcome the effect of the channel on the transmitted signal and provide reliable service for all users. Site measurements are expensive and time consuming and cannot be done in the planning stage of a new building. An alternative is the use of empirical or deterministic models. A variety of these models is presented in the literature from which a selection will be presented in chapter 2, such as Rayleigh fading model, ray tracing models and Finite Difference Time Domain (FDTD) models. The choice of the channel model depends on the type of the environment, the degree of accuracy required as well as the available simulation resources. The use of deterministic models increases the accuracy but requires advanced simulation resources.

Once an appropriate channel model is selected, the channel characteristics can be found for all possible base stations' locations, then a minimum number of base stations must be distributed in the environment to provide the best service to all users with minimum power levels. For this reason, a single performance measure or a combination of performance measures such as the signal strength, the path loss, the signal-to-interference plus noise ratio (SINR) and the bit-error rate (BER) must be formulated into an objective function, also known as a cost function. The variables of this cost function can be the base stations' locations and/or the amount of emitted power. The optimisation of this cost function leads to the base stations' locations and/or emitted power levels that provide the best achievable service. In addition to the base stations' locations and emitted power levels, the number of base stations can be optimised and the minimum number of base stations can be then found. Depending on the number of the variables' combinations for which the cost function is evaluated one can use either a brute force optimisation approach or one of the well-known optimisation techniques. In other words, if the number of the variables' combinations is limited, the cost function is evaluated for all the variables possibilities and then the optimal value is selected. Otherwise, the brute force optimisation approach will be time consuming and an optimisation technique must be used instead, though a sub-optimal solution may be obtained. A large number of optimisation techniques exists each having its own characteristics. In general these techniques can be classified into two categories:

gradient-based algorithms and heuristic-based algorithms. Gradient-based algorithms require first and/or second derivatives whereas heuristic-based algorithms require only the objective function values. Chapter 3 will present a selection of cost functions existing in literature defined based on different performance measures. The majority of those cost functions are optimised using optimisation techniques, with higher preference given to the heuristic based algorithms, thus, the basics of different algorithms will be highlighted in chapter 3.

All models dealing with the base stations' location problem presented so far in literature are based on a single environment configuration, mainly an empty environment with walls the only element modelled. However, the environment is not static. It is subject to changes such as movement of objects or even people which may affect the optimal base stations' locations as well as the power levels. On the other hand, this research is intended to find the optimal base stations' positions and minimal amount of power in an indoor environment. The details of the environment will be taken into consideration, thus furniture will be distributed in the environment and changes like opening doors and windows will be considered. The presence of people will also be considered. The first step before defining the cost function is the selection of the appropriate channel model. To be able to represent the fine details of the environment, a site specific channel model is required, therefore, a sophisticated ray tracing software is selected [3][4]. The software requires the 2D plan of the environment with the permittivity and conductivity of the materials present in the environment. Chapter 4 will describe the details of the ray tracing software in addition to the indoor environment used as the test environment along with its representation using the ray tracing software. The field strength values generated by the software will be validated through site measurements performed in the test environment.

After getting the channel characteristics for all the possible transmitter's positions, the cost function must be defined. The first new cost function optimised in this work is a simple cost function defined based on the path loss values. It consists of the path loss average and standard deviation. As soon as the optimal base stations' positions are found, the minimal amount of power that each base station must emit to provide a predefined coverage percentage is calculated. Chapter 5 will discuss the cost function and the optimal positions obtained when the same environment is considered under different circumstances starting with an empty environment and then adding

furniture and illustrating some of the changes that may occur in the environment. The effect of environment changes on the optimal base stations' locations as well as the minimal emitted power will be shown. The chapter will also discuss the effect of using multiple base stations instead of a single one on the total amount of required power. Although brute-force optimisation is adopted throughout this work, genetic algorithm will be tested and its use will be discussed.

All the cost functions presented in the literature to date including the one that will be presented in chapter 5 ignore the time dispersion parameters. A receiver's position acquiring sufficient signal level can still have problem enjoying the service. This can be due to the time dispersion parameters' values compared to the symbol period. As the delay spread values get higher than the symbol period, the error rate increases and the service worsens. Consequently, optimal base stations' locations obtained based on a cost function defined with the signal level measures alone does not provide the best service as it cannot guarantee the service to all receivers' positions getting enough signal level. The time dispersion parameters must then be included in the cost function definition. Chapter 6 will present three novel cost functions defined based on both the path loss and the rms delay spread values. The same test environment will be used and considered first to be empty. Different cost functions' parameters will be explored and their effect on the optimal base stations' locations will be discussed. Furthermore, the optimisation process will be repeated for different numbers of base stations where the environment will be served by one, two or three base stations.

The environment is assumed to be empty as it is more likely that the optimal base stations' locations will be found in the design stage when the furniture location is unknown which will make the optimal positions ideal. In other words, the presence of furniture and people in the environment will highly affect the channel characteristics and different optimal base stations' positions may be obtained. For this reason, the same approach regarding the environment changes adopted in chapter 5 will be used in chapter 7. Different environment configurations will be considered starting by adding furniture to the environment then modelling the opening of doors and windows in addition to the presence of people in the environment. The effect of environment changes on the optimal base stations' locations when the cost functions defined in chapter 6 are used with various parameters will be explored when one, two or three base stations are serving the environment.

Any indoor environment is subject to continuous changes. Finding the optimal base stations' locations after each change and moving the base stations accordingly is not practical. Chapter 8 will discuss some possible solutions where the base stations adapt to the environment changes. Thus the base stations should be able to detect these changes mainly by monitoring the power of the receiver and then act appropriately. Several solutions are proposed; the first is increasing the power emitted by the base stations. In this case the receiver may get higher signal level and regain service. Another proposed solution is to change the antenna polarisation so different signal distribution is obtained which may improve the service at certain receivers' locations. The last way suggested in chapter 8 to reduce the environment changes effect is by providing the base stations with the ability to move for a limited distance in different directions. This can be useful as in some cases the effect of the environment changes on the optimal base stations' locations is a movement for a short distance toward a closer possible base station's location. The three techniques will be applied to the test environment and their effectiveness will be discussed.

The closing chapter (chapter 9) will present conclusions of this work in addition to some suggestions for future work.

Chapter 2: Channel Modelling

2.1 Introduction

A wireless signal propagating through an environment may undergo reflection, refraction, diffraction or scattering that will attenuate the signal and change its initial direction of propagation. The signal at the receiver end will then be the combination of different attenuated and delayed versions of the transmitted signal. These signals may add constructively or destructively thus the transmitted information may not be delivered properly to the receiver. Modelling the effects of this process on the received signal is known as the channel modelling.

On the other hand, the design of wireless communication systems requires proper knowledge of the channel characteristics such as the path loss, delay measures, in addition to quality measures like the error rate. The first way that might come to mind is site measurements. However site measurements are very expensive and time consuming. This is why researchers tried to come up with alternative methods. These methods can be classified into two types. The first type is statistical or empirical and the second type is site-specific or deterministic. Deterministic models require detailed information about the environment geometry, furniture location and material type of walls, windows and doors as well as that of all constituents of the environment (permittivity, conductivity and permeability) whereas empirical models do not. Empirical models are simple to implement, however, they lack accuracy whereas deterministic models are more accurate but complex to implement due to their simulation burden and memory requirements. The selection of the channel modelling technique depends on the environment type and complexity as well as the required accuracy and the available simulation resources.

The chapter will present a summary of different empirical and deterministic channel modelling techniques. It will start with the definition of some channel characteristics' parameters. The basic propagation mechanisms (reflection, refraction, diffraction and scattering) will be also reviewed. The empirical models will then be presented. On the other hand, a summary of some variations of the principal deterministic channel modelling techniques will be discussed mainly, ray tracing and Finite Difference Time Domain (FDTD) as well as a combination of both techniques.

The chapter also includes a brief examination of the use of neural networks to model the wireless channel. Finally, the effect of dielectric properties on the channel characteristics' parameters is explored.

2.2 Channel Characteristics Parameters

The wireless channel is characterised by different parameters. The main parameter is the path loss that shows the amount of the signal attenuation. It is computed in dB as follows [1]:

$$PL(dB) = 10 \log_{10} \left(\frac{P_t}{P_r} \right) \quad (2.1)$$

where P_t and P_r are the transmitted and received powers respectively.

While propagating through the channel, the transmitted signal will confront different obstacles and may be reflected, refracted, diffracted or scattered. Consequently, multiple attenuated copies of the transmitted signal will arrive at the receiver at different time. These delayed versions of the signal may cause inter-symbol interference and deteriorate the channel performance by increasing the error rate, thus the time delay must be quantified. The time dispersion parameters are the mean excess delay, the rms delay spread and the maximum excess delay. Assuming that the channel is time invariant, the mean excess delay is defined as [1]:

$$\bar{\tau} = \frac{\sum_{k=0}^n P(\tau_k) \tau_k}{\sum_{k=0}^n P(\tau_k)} \quad (2.2)$$

where $P(\tau_k)$ is the power of the k^{th} multipath component arriving at time τ_k relative to the first received signal arriving at $\tau_0 = 0$. The rms delay spread is defined as [1]:

$$\sigma_{\tau} = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \quad (2.3)$$

with

$$\overline{\tau^2} = \frac{\sum_{k=0}^n P(\tau_k) \tau_k^2}{\sum_{k=0}^n P(\tau_k)} \quad (2.4)$$

As for the maximum excess delay, it is defined as the time difference between the first arriving signal and the last arriving signal having a power X dB less than that with the highest power [1].

Based on the time dispersion parameters, the channel can be classified as a flat fading channel or frequency selective fading channel. As a general rule, when

$$T_S < 10 \sigma_\tau \quad (2.5)$$

with T_S being the symbol period, the channel is frequency selective and the received signal suffers from intersymbol interference, otherwise, the channel is flat [1].

On the other hand, other parameters are used to classify the channel such as the coherence bandwidth in addition to the parameters that illustrate the time varying nature of the channel mainly the Doppler spread and coherence time [1]. Based on the Doppler spread, the channel can be either a fast or slow fading channel.

2.3 Basic Propagation Mechanisms

Some deterministic models are based on geometrical optics, this is why it is important to start with a brief review of the four basic propagation mechanisms that are: reflection, refraction, diffraction and scattering.

2.3.1 Reflection and Refraction

Reflection occurs when the electromagnetic wave impinges an object having a very large dimension compared to the signal wavelength, for example: surface of walls, ground and furniture. Refraction occurs when the electromagnetic wave travels from one medium to another. This will cause a change in the direction of the wave as long as the incidence is not normal. Unless the surface is totally reflective, reflection and refraction are usually linked together in a sense that whenever there is reflection there will be refraction. For example, assume that an electromagnetic wave travelling in a room hits a wall, part of the ray will be reflected back and another part will be transmitted inside the wall. This transmitted wave will be refracted because it has moved between two different materials (air and the wall). The refracted ray is usually denoted as the transmitted ray.

The reflection coefficient, also known as the Fresnel reflection coefficient Γ , is defined as the ratio of the reflected electrical field to the incident electrical field [1]:

$$\Gamma = \frac{E_r}{E_i} \quad (2.6)$$

The reflection coefficient varies based on the permittivity, the permeability and the conductivity of the material (ϵ, μ and σ respectively), the incident angle θ_i , the polarisation of the wave and the electromagnetic wave frequency. Note that the permittivity ϵ of a perfect dielectric is usually expressed in terms of a relative permittivity ϵ_r [1]:

$$\epsilon = \epsilon_0 \epsilon_r \quad (2.7)$$

with ϵ_0 being a constant equal to 8.85×10^{-12} F/m.

For the case of lossy materials, a complex permittivity is defined as follows:

$$\epsilon = \epsilon_0 \epsilon_r - j \frac{\sigma}{2\pi f} \quad (2.8)$$

Figure 2.1 and Figure 2.2 show the incident, reflected and transmitted electric fields for the parallel and the perpendicular polarisations. In the case of parallel polarisation, the electric field is normal to the reflecting surface whereas in the perpendicular polarisation, the electric field is parallel to the reflecting surface.

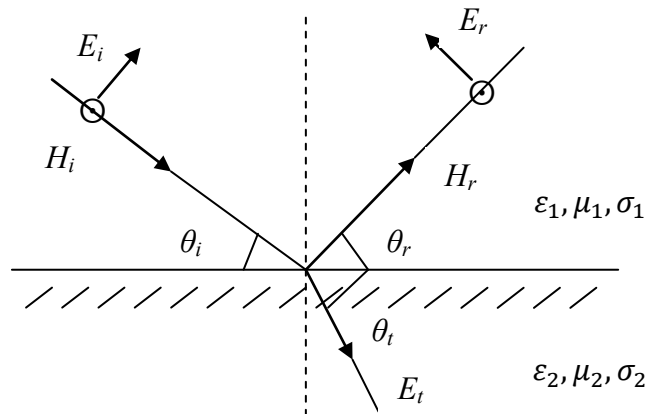


Figure 2.1: Reflection (parallel polarisation)

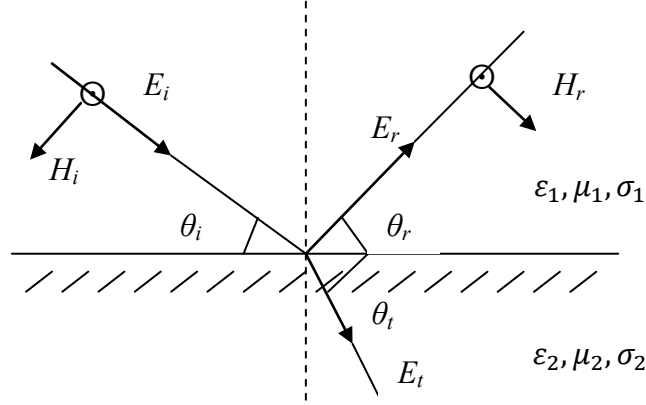


Figure 2.2: Reflection (perpendicular polarisation)

The parallel reflection coefficient is:

$$\Gamma_{\parallel} = \frac{\eta_2 \sin \theta_t - \eta_1 \sin \theta_i}{\eta_2 \sin \theta_t + \eta_1 \sin \theta_i} \quad (2.9)$$

The perpendicular reflection coefficient is:

$$\Gamma_{\perp} = \frac{\eta_2 \sin \theta_i - \eta_1 \sin \theta_t}{\eta_2 \sin \theta_i + \eta_1 \sin \theta_t} \quad (2.10)$$

η is the intrinsic impedance of the medium and it is defined as:

$$\eta = \sqrt{\frac{\mu}{\epsilon}} \quad (2.11)$$

Given the incident angle, one can use Snell's Law to find the transmission angle θ_t :

$$\sqrt{\mu_1 \epsilon_1} \sin(90 - \theta_i) = \sqrt{\mu_2 \epsilon_2} \sin(90 - \theta_t) \quad (2.12)$$

As for the reflection angle θ_r , it is equal to the incidence angle θ_i .

The reflected and transmitted electrical fields are then:

$$E_r = \Gamma E_i \quad (2.13)$$

$$E_t = (1 + \Gamma) E_i \quad (2.14)$$

Note that the reflection coefficient is either Γ_{\parallel} or Γ_{\perp} depending on the electrical field polarisation and that for general cases, a superposition of the parallel and the perpendicular values can be done.

2.3.2 Diffraction

Diffraction occurs when an obstruction with a sharp edge exists between the transmitter and the receiver. Due to the complexity of the geometrical theory of diffraction (GTD), diffraction is usually modelled based on the knife-edge model [1][5]. In this model, the refracting object is considered to be thin. Figure 2.3 shows the geometry of the knife-edge diffraction model.

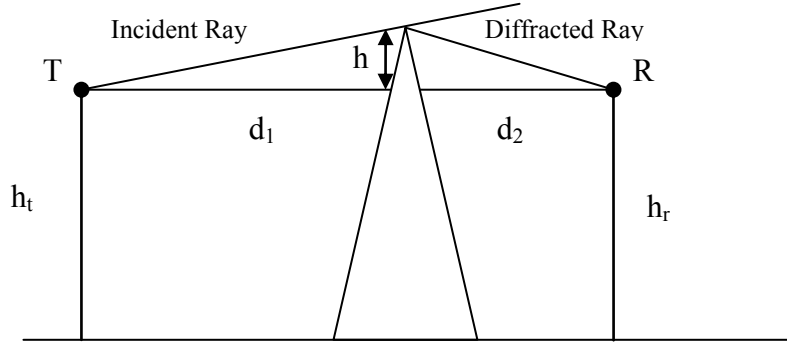


Figure 2.3: Knife-edge diffraction

The Fresnel-Kirchoff diffraction parameter is:

$$\nu = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (2.15)$$

where λ is the wavelength.

The diffraction path loss as a function of the Fresnel-Kirchoff diffraction parameter is given by [1]:

$$L(\nu)dB = \begin{cases} 0 & \nu \leq -1 \\ 20 \log(0.5 - 0.62\nu) & -1 \leq \nu \leq 0 \\ 20 \log(0.5e^{-0.95\nu}) & 0 \leq \nu \leq 1 \\ 20 \log(0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}) & 1 \leq \nu \leq 2.4 \\ 20 \log\left(\frac{0.225}{\nu}\right) & \nu > 2.4 \end{cases} \quad (2.16)$$

2.3.3 Scattering

Scattering occurs when the radio wave hits an object with a small dimension compared to the signal wavelength. It is also related to the roughness of the surface where a surface is considered to be rough if its protuberances are greater than a critical height h_c that is [1]:

$$h_c = \frac{\lambda}{8 \sin \theta_i} \quad (2.17)$$

The signal is then reradiated in multiple directions (Figure 2.4). Thus, the reflection coefficient of a rough surface is that of a flat surface multiplied by a scattering loss factor ρ_s :

$$\Gamma_{rough} = \rho_s \Gamma \quad (2.18)$$

$$\rho_s = \exp \left[-8 \left(\frac{\pi \sigma_h \sin \theta_i}{\lambda} \right)^2 \right] I_0 \left[8 \left(\frac{\pi \sigma_h \sin \theta_i}{\lambda} \right)^2 \right] \quad (2.19)$$

where σ_h is the surface height standard deviation and I_0 is the zero order modified Bessel function of the first kind.

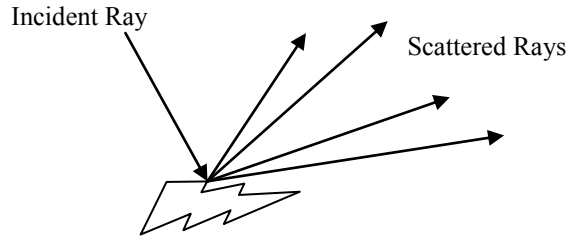


Figure 2.4: Scattering

2.4 Statistical Channel Models

The large scale fading is empirically modelled using a path loss factor. The first empirical model presented in this section is the piecewise linear model also known as the multi-slope model. It is used to model outdoors (microcells) and indoor channels.

The dual slope model is the special case of the piecewise model with two segments and one break point at a distance d_c . The received power at a distance d is then [5]:

$$P_r(d)dB = \begin{cases} P_t + K - 10\gamma_1 \log\left(\frac{d}{d_0}\right) & d_0 \leq d \leq d_c \\ P_t + K - 10\gamma_1 \log\left(\frac{d_c}{d_0}\right) - 10\gamma_2 \log\left(\frac{d}{d_c}\right) & d > d_c \end{cases} \quad (2.20)$$

where P_t is the transmitted power, K is the path loss factor, γ_1 is the path loss exponent for the distance between the reference distance d_0 and the critical distance d_c and γ_2 is the path loss exponent at a distance greater than d_c . Regression based on empirical measurements is used to find the values of the path loss exponents as well as the path loss factor K and the critical distance.

Another empirical channel model is the attenuation factor model. This model takes into consideration the attenuation due to floors and to partitions with different building materials. The path loss is then:

$$PL(d) = PL(d_0) + 10\gamma \log\left(\frac{d}{d_0}\right) + FAF + \sum_{i=1}^P PAF_i \quad (2.21)$$

where γ is the path loss exponent, FAF is the floor attenuation factor and PAF_i is the partition attenuation factor of the i^{th} partition. The values of FAF and PAF are selected from tables available in [1]. Note that the partition attenuation factors are selected depending on the partition material type.

On the other hand, small scale fading is statistically modelled based on probability distributions. The most commonly used distributions to model the signal envelope amplitude are the Rayleigh and the Ricean distributions. When there is a dominant line-of-sight between the transmitter and the receiver, the signal envelope is considered to follow a Ricean distribution whereas in the absence of a direct line-of-sight, the envelope will follow a Rayleigh distribution. The following two equations are the probability density functions of the Rayleigh and Ricean distributions respectively [1]:

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) & r \geq 0 \\ 0 & r < 0 \end{cases} \quad (2.22)$$

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right) & r \geq 0, A \geq 0 \\ 0 & r < 0 \end{cases} \quad (2.23)$$

where r is the envelope of the received signal, $2\sigma^2$ is the average diffuse power, A is the peak amplitude of the dominant line-of-sight and I_0 is the zero order modified Bessel function of the first kind. Figure 2.5 shows the probability density function of the Rayleigh distribution for different average diffuse power values ($2\sigma^2$). It can be seen that as the average diffuse power is increased, the probability density function is more spread. As for the Ricean probability density function, it is shown in Figure 2.6 for different line-of-sight peak amplitude and average diffuse power values. When the line-of-sight peak amplitude is increased, the probability density function is shifted eastward whereas when the average diffuse power is increased the distribution is more spread. Note that when A tends to 0, the Ricean distribution converges to the Rayleigh distribution.

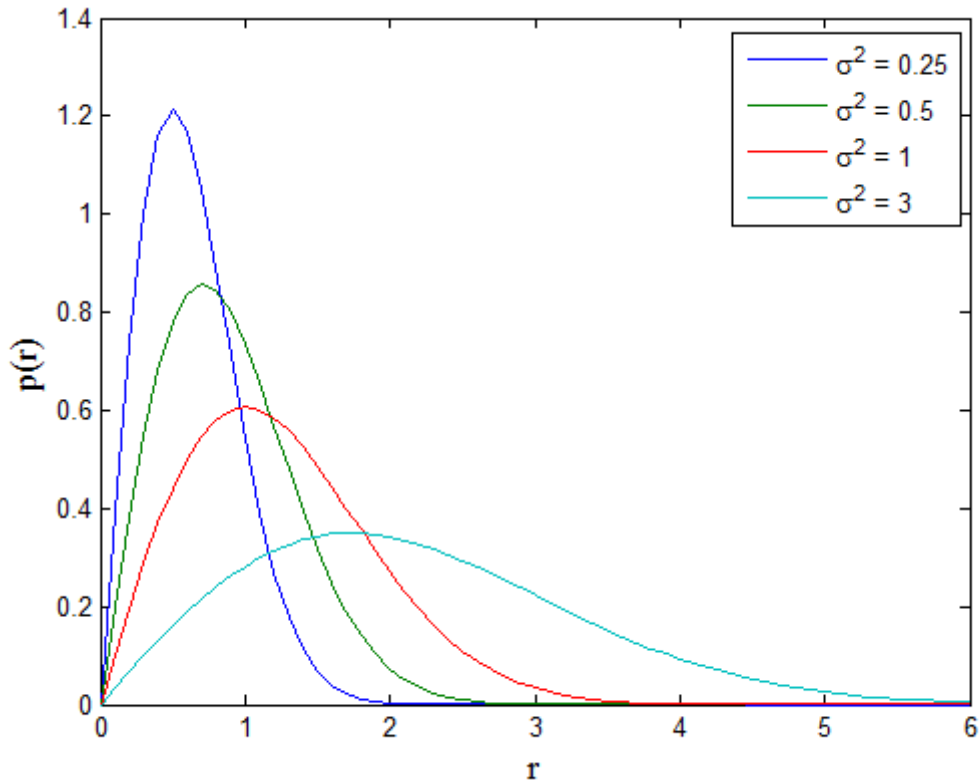


Figure 2.5: Probability density function of the Rayleigh distribution for different average diffuse power values ($2\sigma^2$)

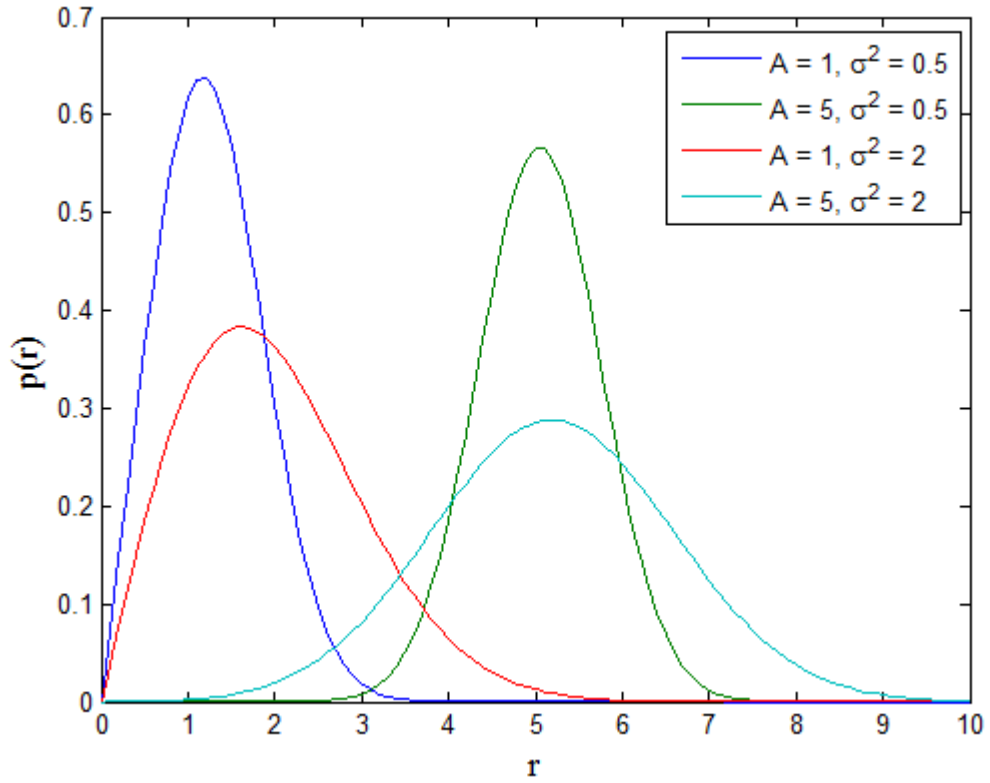


Figure 2.6: Probability density function of the Ricean distribution for different line-of-sight peak amplitude (A) and average diffuse power ($2\sigma^2$) values

A 7 ray empirical based model is presented in [6]. The 7 rays correspond to the following paths: the direct line-of-sight, the reflection off the ceiling, the reflection off the floor and the reflections off the 4 surrounding walls. The signal arriving from each of these paths is generated as the transmitted signal attenuated by a random zero mean Gaussian factor between 0 and 1. The phase is also randomised by adding zero mean Gaussian phase between 0 and 2π to the transmitted signal. The rate of both randomisations is chosen based on measurement of the delay spread and it is 6 Hz. This model is limited. It assumes that the environment is a rectangular empty room so that the 7 rays become enough. This is an unrealistic scenario. One cannot predefine the number of rays to estimate the channel characteristic.

2.5 Deterministic Channel Models

The main deterministic models available in literature are ray tracing and Finite Difference Time Domain (FDTD). Both techniques give accurate channel modelling

even though FDTD is more accurate but requires much more simulation time. This section will introduce some of these models.

2.5.1 Ray Tracing

Ray tracing is one of the most used site-specific channel modelling techniques. It is based on geometrical optics where the energy is considered to be emitted through rays. It requires information regarding the geometry of the environment, material characteristics (permittivity and conductivity), as well as the transmitter and receiver positions. The main types of ray tracing are: image method and ray shooting method [7].

In image-based ray tracing, images of the source are produced at all reflecting planes to act as secondary sources. The authors in [8] and [9] presented an image based ray tracing technique in which for each transmitter's location, all obstacles are considered as possible reflectors and images are created, the location of these transmitter's images are stored in arrays to be used in the field strength's calculations. These arrays require a large amount of memory. Thus image methods are suitable only for simple environments [7].

In ray shooting method, a large number of rays is launched in all directions. If the ray tracing is performed in 2D, rays are radiated from the transmitter in all directions in a plane. The angle between any two adjacent rays is ϕ . The size of this angle can be controlled and its value affects the accuracy of the predicted field strength as well as the simulation time. As the angle becomes smaller, the accuracy and the simulation time are increased. Each ray can be treated as a binary tree with the interaction with an obstacle being the node [7][10]. The ray is then split into two rays and the process repeats until the ray strength reaches a predefined threshold value, a certain number of reflections is reached, the ray diverts outside a given area or the ray reaches the receiver. If the ray tracing was performed in 3D, a sphere is used instead of a plane.

One of the challenges in ray tracing is the selection of a correct reception sphere. If the reception sphere radius is large, double counting may occur. If the radius is small, some rays will not be counted (zero counting). Both double counting and zero counting will introduce errors in the received signal power and affect the accuracy of the model. It is stated in [11] that the radius of the reception sphere should be at least $1/\sqrt{3}$ the distance between adjacent rays. However this radius will lead to double counting with a

probability 20.9%. Instead, a radius of 1/2 the distance between adjacent rays is used. It was shown that double counting will not occur but zero counting will occur with a probability of 4.97%. Thus the probability of counting errors is reduced and the accuracy of the ray tracing model is improved.

A variety of ray tracing techniques exists. Some are performed in 2D and others in 3D. Some take into consideration all propagation mechanisms with the exception of scattering as it can be neglected in an indoor environment due to the high frequency used, while others use only reflection. In addition, some models do not include the effect of furniture in the environment.

The ray tracing model presented in [10] takes into consideration the presence of doors and windows in the environment and ignores furniture. The environment is split into $1 \text{ cm} \times 1 \text{ cm}$ pixels. A ray takes part in the calculation of the channel impulse response at a given pixel if the ray sector covers any part of the pixel. Taking reflection and transmission into consideration, the channel impulse response is defined as follows:

$$\underline{h}^{x,y}(t) = \sum_{n=1}^{N^{x,y}} \left[\left(\prod_{u=1}^{M_{rn}^{x,y}} \Gamma_{nu}^{x,y} \cdot \prod_{v=1}^{M_{pn}^{x,y}} P_{nv}^{x,y} \right) \frac{1}{r_n^{x,y}} \cdot e^{-j\omega \tau_n^{x,y}} \cdot \delta(t - \tau_n^{x,y}) \right] \quad (2.24)$$

where: $N^{x,y}$ is the number of rays reaching the pixel located at (x, y) ; $M_{rn}^{x,y}$ and $M_{pn}^{x,y}$ are the number of reflections and penetrations ray n encountered with $\Gamma_{nu}^{x,y}$ and $P_{nv}^{x,y}$ their corresponding coefficients respectively; $r_n^{x,y}$ is the path length of ray n ; $\tau_n^{x,y}$ is the excess run time of ray n .

Another ray tracing software is presented in [3] and [4] where the environment is represented by $n_x \times n_y$ equal dimension rectangular cells. The size of the cell can be controlled by the user. For each cell corresponds a given permittivity and conductivity. The software simulation is done in two stages. The first stage corresponds to ray tracing where rays are launched over the 360° range. Every time a ray reaches a cell boundary, the incidence angle, the path length as well as the attenuation due to reflection and refraction and other necessary information are stored. The ray tracing continues until its strength falls below a predefined threshold level. The second stage is the field reconstruction in which for each receiver's position, a check is done to find the “ n ” rays that illuminate the receiver and the total field strength is calculated using:

$$E = \sum_n E_n \quad (2.25)$$

$$S(dB) = 10 \log_{10} |E|^2 \quad (2.26)$$

$$E_n = \left(\frac{A_n}{r_n} e^{-(r\alpha)_n} \right) e^{j(\beta r)_n} \quad (2.27)$$

where r_n is the path length, A_n is the attenuation due to reflection and refraction and it is calculated based on the reflection and refraction coefficients ρ_i and τ_j respectively:

$$A_n = \prod_i (\rho_i)_n \prod_j (\tau_j)_n \quad (2.28)$$

αr is the attenuation due to the medium and it is calculated as the summation of the product of the attenuation and the path length over all mediums the ray passed through:

$$\alpha r = \sum_i \alpha_i r_i \quad (2.29)$$

$$\alpha_i = \text{Re} \sqrt{j\omega\mu_i(\sigma_i + j\omega\varepsilon_i)} \quad (2.30)$$

μ_i , σ_i and ε_i are the permeability, conductivity and permittivity of the medium i .

Finally, βr is calculated as follows:

$$\beta r = \sum_i \beta_i r_i \quad (2.31)$$

with β_i being the phase constant in medium i :

$$\beta_i = \text{Im} \sqrt{j\omega\mu_i(\sigma_i + j\omega\varepsilon_i)} \quad (2.32)$$

The authors in [12] presented 3D ray tracing software. The geometry of the environment is specified through a graphical interface in which the 3D coordinates of walls and partitions should be supplemented along with their real and complex permittivities in order to calculate the real and complex reflection and transmission coefficients required for the field strength calculation. The number of reflections a ray can come across is specified by the user. The ground is modelled as a borderless perfect conductor. The software provides two possible simulation types: a fixed transmitter location or a mobile receiver moving along a predefined linear path. This software bypassed the presence of furniture, doors and windows in the environment.

The WiSE simulator, another example of 3D ray tracing software developed by Lucent Technologies provided accurate channel modelling compared to empirical measurements as shown in [13] and [14].

Compared to 2D ray tracing, 3D ray tracing gives more accurate results but with an increased simulation time. To reduce the simulation time of 3D ray tracing while maintaining high accuracy, the authors in [15] adopted a combination of a 2D ray tracing at the horizontal and the vertical planes. Two cases should be considered: the line of sight (LOS) and the non-line of sight (N-LOS). For the LOS situation, 2D ray tracing is applied to the horizontal and the vertical planes in which the transmitter and the receiver are and results are summed. For the N-LOS situation, it is not possible to have the transmitter and the receiver in the same vertical plane, thus $(m-1)$ transmitter's images having direct path with the receiver are defined with m being an integer greater than 2 selected based on the geometry of the environment. The 2D ray tracing is then performed $(m-1)$ times in the vertical plane. Results of the vertical planes and horizontal plane are then summed. Comparing the simulation time, it is proportional to N^3 for the 3D ray tracing whereas it is proportional to $2N^2$ for the combined horizontal and vertical 2D ray tracing with direct LOS and to mN^2 with N-LOS where N is the number of emitted rays. Although it appears that this combined ray tracing technique reduces the simulation time, it can be noticed that the ray tracing should be done for every receiver position instead of ray tracing the whole environment and then reconstructing the field at every receiver position, which will increase the overall simulation time again.

An alternative way for decreasing the computation time required for the 3D ray tracing was presented in [16]. The authors suggested dividing the 3D environment into tetrahedrons using the objects' vertices. The ray is tracked and whenever it hits a surface of the tetrahedron, a check is done to see whether this surface represents an object and consequently the transmission and reflection coefficient will be calculated.

A threshold value for the signal level is usually used as the stopping criterion for the ray tracing in order to lower the simulation time. The choice of this threshold is critical and affects the accuracy of the signal strength prediction. If the threshold value is high, fast simulation time is obtained at the cost of low accuracy whereas if the threshold value is low, high accuracy is obtained at the cost of an increased simulation time. Thus the authors in [17] found an approximate that helps to select an appropriate

threshold to decrease the simulation time while maintaining notable accuracy. The value of the positive tenth-order threshold is expressed in terms of the maximum number of required reflections n and the average of the reflection coefficients of materials in the environment Γ and it is:

$$p > -2n \log_{10}|\Gamma| \quad (2.33)$$

For example, if p is 3, the threshold value will be -30dB.

2.5.2 Finite Difference Time Domain By Yee Method

Finite Difference Time Domain (FDTD) numerically solves Maxwell's equations. It provides the electric field at every point in the environment. The six partial differential Maxwell's curl equations are transformed into difference equations with respect to the fields' positions to be numerically solved based on the Yee algorithm [18]. Thus the space is divided into 3D cells where the electric field components are on its edges and the magnetic field components are on its centres. Consequently, every electric field component is centred around four magnetic field components and vice versa. In addition, the electric and magnetic fields components are centred in time. In other words, the electric field components are calculated and stored in memory, and then the magnetic field components are calculated using the previously calculated electric field components and also stored to be used in the next electric field components' calculations. This process continues until the electric and magnetic wave components are calculated over the specified time interval. To reduce the problem into 2D problem, two possible modes can be used: the transverse-magnetic mode with respect to z (TM_z) and transverse-electric mode with respect to z (TE_z). In the TM_z mode, only three components remain from the magnetic and electric fields: H_x , H_y and E_z . In the TE_z mode, the three remaining components are E_x , E_y and H_z [19]. The trickiest part in FDTD technique is how to truncate the space lattice, as computers cannot store an infinite amount of data, without affecting the electromagnetic field calculations results due to external reflections. This is usually done by adding an artificial boundary that should absorb all the power by making the reflection coefficient close to zero and is known as the absorbing boundary conditions (ABC). The ABC can be classified into two categories. The first is an analytical boundary condition applied on the electromagnetic field at the boundaries of the space lattice. A commonly used ABC of this type is the Mur absorbing boundary condition. The second type is based on

adding layers of an absorbing material to the external cells. This type is known as the perfectly matched layer (PML). Note that the first type is simpler than PML however PML highly reduces the external reflections. [19][20]

FDTD is suitable for small regions with complex structure. It is more accurate than ray tracing but requires a huge amount of memory and too much calculation. The authors in [21] compared the simulation time when ray tracing and FDTD are applied to a room with dimensions of $7.39\text{ m} \times 7.39\text{ m} \times 3.66\text{ m}$. The ray tracing simulation time was 4 minutes 55 seconds whereas that of FDTD was 14 hours 32 minutes 22 secs. Consequently, the FDTD simulation time was 177.43 times more than that of ray tracing.

In the case of curved surfaces such as tunnels [22], ray tracing is not efficient as it requires huge computation time since the number of emitted rays should be increased. Thus, it is better to use FDTD instead of ray tracing for such environments. Note that with the advancement of technology in terms of simulation resources, the authors of [23] applied 2D FDTD to model the radio wave propagation in an 8 floors building.

The authors in [24] applied the 2D FDTD technique with TM_z mode to a $30\text{ m} \times 30\text{ m}$ indoor environment with a $5\text{ cm} \times 5\text{ cm}$ cell size. The absorbing boundary condition was Mur's second condition. It was shown that with accurate material characteristics, FDTD gave accurate results compared to measurements. FDTD with the TM_z mode was also used in [25] but with first order boundary conditions and a $3\text{ cm} \times 3\text{ cm}$ cell size. Acceptable correspondence was achieved between the simulated and measured results. However, if 3D FDTD was used instead of 2D, the effect of floor and ceiling reflections would be included which will improve the results. The FDTD applied in [26] differs from the previously mentioned FDTD examples by the use of 10 cells perfectly matched layer. It was also shown that it produces accurate results. Note that in all these FDTD applications, the authors did not mention anything about the simulation burden and did not compare the obtained results with a ray tracing algorithm to show if it is worse using the FDTD for the type of environment they simulated.

2.5.3 Hybrid FDTD and Ray Tracing

To benefit from the advantages of both ray tracing and FDTD, a combination of both techniques is possible. The environment will be split into different parts depending

on its complexity. FDTD is then applied to complex areas where ray tracing is not accurate enough and ray tracing is applied to wide areas where it can provide an accurate result with a lower simulation time compared to FDTD. Examples of the use of the hybrid technique are presented in [27] and [28]. The ray tracing used takes into consideration the direct, reflected, transmitted and refracted rays. The region in which FDTD method needs to be applied is enclosed by a virtual box. This region is then divided into rectangular grid. The distance between a cell node on the incident plane and the incoming ray is calculated. If it is less than $\frac{\theta d}{\sqrt{3}}$ for 3D or $\frac{\theta d}{2}$ for 2D with θ and d being the ray tube angle and the distance crossed by the ray respectively, then this ray should be added to the rays entering the region at this node. Thus, at each node, the electric field is the summation of that of all the rays illuminating the node. The electric field of all nodes will then propagate within the specified region based on FDTD with PML or Mur used as an absorbing boundary condition in [27] and [28] respectively. The effectiveness of this hybrid technique was verified only in [28] where simulation examples were presented and compared with those of the pure ray tracing and FDTD. This makes [28] well thought-out and more convincing compared to [27]. The hybrid technique is shown to be sometimes even faster than ray tracing when the number of receivers' locations in the ray tracing is large. The hybrid method is also shown to be less sensitive to the ray tube angle than ray tracing alone. This can be explained by the fact that, in the hybrid method, FDTD is applied to the complex parts of the environment and these are the parts that are more affected by the ray tube angle.

2.5.4 Neural Network

Neural networks are sometimes used to model wireless channels. The two commonly used neural network models are the multilayer perception model and the radial basis function model. The inputs of the neural network are generally information regarding the geometry of the environment as well as transmitters' and receivers' positions. Its output is the signal strength. A radial basis neural network model is better than the multilayer perception model in term of convergence during the training process [7].

Both the multilayer perception and the radial basis function models were used in [29], [30] and [31]. The inputs of the models are only the base stations' and receivers' coordinates and no information regarding the geometry of the environment is used.

Field strength measurements were done in order to train the neural network. Simulation showed that radial basis function neural network has better performance compared to both the multilayer perception neural network as well as the ray tracing model. However, there is doubt about the effectiveness of a neural network model trained by measurements. For every new environment, measurements should be done in order to retrain the neural network model, this will even happen if any change occurs in the environment. Thus, it can be argued that a neural network approach will be less efficient than ray-tracing.

2.6 The Effect of Dielectric Properties

A mono-static measurement system was developed based on ground penetrating radar (GPR) principle in order to measure the material dielectric parameters in [32]. The permittivity and conductivity of the walls of an indoor environment were then varied and 3D ray tracing software was used to predict the path loss and delay spread at some receivers' locations. The same approach was done in [33] but the permittivity and conductivity of all environment materials were varied. It was shown that the path loss for an environment with LOS is not highly affected by dielectric parameters' change whereas for the Non-LOS environment, it is sensitive to dielectric parameters. As for the delay spread, the results of both environments are highly sensitive to the dielectric parameters' change. Hence, the dielectric properties of the material affect the channel modelling process and they must be carefully selected.

2.7 Conclusions

The wireless communication channels can be characterised using either deterministic or empirical models. Empirical models are simple to implement and do not require detailed information concerning the environment whereas deterministic models require detailed information about furniture locations and material types. In terms of accuracy, deterministic models are more accurate but with high computation time and memory requirements. The most used deterministic models are the ray tracing and the FDTD techniques. Both techniques can be implemented in 2D or 3D. It is

obvious that the addition of the third dimension improves the accuracy but highly increases the simulation burden.

Ray tracing is based on geometrical optics where rays are launched and tracked as they propagate through the environment and hit the environment constituents. The propagation mechanisms taken into consideration in the ray tracing examples discussed in this chapter are the reflection and refraction. The ray tracking may last until the signal level falls below a certain cut-off value or until a certain number of reflections is achieved. The more the ray is traced, the higher the achieved accuracy is and more simulation time is required.

FDTD numerically solves Maxwell's equations based on Yee algorithm. Compared to ray tracing, FDTD is more accurate at the cost of an increased computation time and storage usage. However, for simple environments, while comparing the added simulation burden to the extra accuracy FDTD provides, one would use ray tracing. Thus, one way of benefitting of the advantages of both techniques is to combine them by splitting the environment into multiple regions depending on its complexity. FDTD is then applied to complex and small regions whereas ray tracing is applied to the rest where using FDTD will not noticeably increase the accuracy.

Finally, the channel modelling is sensitive to the selection of dielectric properties of materials available in the environment. Proper selection of these values results in a more realistic channel characteristics.

Chapter 3: Review of Approaches for Optimising The Base Stations' Locations

3.1 Introduction

The performance of a wireless communication system is greatly affected by the position, the amount of emitted power and the number of the base stations serving the environment. Therefore, proper design of a wireless communication system requires knowledge of the minimum number of base stations, where to place them, and how much power should each base station emit in order to provide reliable service to all receivers at the lowest cost. The problem can be modelled as an optimisation problem with the cost function being expressed in terms of a single or a combination of many factors such as the signal strength, the path loss, quality-of-service (QoS), coverage area and co-channel interference. These factors can be obtained based on empirical or deterministic channel models. As for the variables, they can be the positions and/or the power of the base stations serving the environment. However, if the positions and the power of the base stations are used together as variables of the cost function, the optimisation process becomes very complex, thus the optimisation is usually done with either the locations or the power of the base stations separately. Mainly, the optimal positions can be found first and then the minimal power corresponding to the optimal positions is obtained. The number of the base stations can also be used as a variable while defining the cost function and must be minimised. The literature contains various cost function models along with their optimisation for both outdoor and indoor environments. This chapter will summarise a selection of those models focusing mainly on those intended for indoor environments. In most cases, different optimisation algorithms are used and their performance is compared thus a summary of these optimisation techniques will be presented in this chapter.

3.2 Optimisation Techniques Overview

Most cost functions that will be defined in this chapter are maximised or minimised using optimisation techniques, thus a review of these techniques is presented in this section.

Optimisation techniques can be classified into two main categories: gradient based algorithms and heuristic based algorithms. The gradient based algorithms require the use of the first order derivatives also known as the gradient or the second order derivatives known as the Hessian matrix whereas the heuristic based algorithms require only objective function values.

Steepest descent is a popular optimisation technique that is widely used in practical applications because of its simplicity. It uses only the first order derivatives to direct the search. However, this is not always efficient. If higher order derivatives are used, the search algorithm may result in better performance [34]. Newton's method, also called Newton-Raphson method, uses first and second order derivatives. It has better performance compared to steepest descent provided that the initial point is close to the optimal point [34].

Conjugate direction methods are considered intermediate between steepest descent and Newton's method. They have better performance compared to steepest descent but they are not superior to Newton's method. However, they usually do not require Hessian matrix evaluation [34].

To overcome the disadvantage of Newton's method lying in the calculation of the Hessian matrix and its inverse, one can use Quasi-Newton's methods. Quasi-Newton's methods approximate the inverse of the Hessian matrix at each iteration instead of calculating its exact value. They are similar to Newton's method with the need to add an update formula for the inverse Hessian matrix approximation [34].

All the optimisation algorithms just mentioned in this section are gradient based algorithms. On the other hand, heuristic based optimisation algorithms are commonly used in optimising the location of base stations within an environment. The first heuristic based algorithm defined in this section is the Nelder-Mead simplex algorithm. It is based on the use of simplex generation in order to find the optimal solution where a simplex is formed by the collection of $n+1$ points. It can be for example a line segment, a triangle or a tetrahedron. The function values are evaluated at the vertices and the vertices are iteratively updated based on four possible operations that are reflection, expansion, contraction (outside contraction or inside contraction) as well as shrinkage depending on their corresponding cost function values [34].

Another heuristic based optimisation algorithm is simulated annealing. Annealing is the thermal process during which a solid is heated to reach a maximum temperature where the solid melts then its temperature slowly decreases until the solid attains a state with minimal energy. In simulated annealing, solutions are equivalent to the state of the solid and the cost of the solution is equivalent to the energy of the state. A control parameter is used to act as the temperature. Given an initial solution, a new solution is found based on a predefined neighbour function. The new solution may or may not be accepted depending on its cost. In addition to solutions that improve the cost function, simulated annealing accepts solutions that deteriorate the cost function to a certain extent. For large control parameter values, a large number of deteriorating solutions is accepted. As the control parameter is decreased, a smaller number of deteriorating solutions is accepted. Finally, when the control parameter approaches zero, no more deteriorating solutions are accepted. This feature helps simulated annealing algorithm to avoid falling into a local minimum. The update of the control parameter values and the number of possible transitions at each value of the control parameter are governed by a cooling schedule [35][36].

Particle swarm optimisation (PSO) algorithm differs from the previous algorithms by the fact that instead of updating a single solution from iteration to iteration, a population composed of d elements is updated. This population is called a swarm and each element of this swarm is called a particle. For each particle there corresponds a position and a velocity. Each particle keeps a record of the best position it has visited (the position corresponding to the optimum objective function value) denoted personal best. The best among all positions visited so far by all particles is also recorded as global best. The movement of each particle is controlled by its own best position as well as the global best position trying to push the particle to an optimal position. This is done by introducing the particle best position and the global best position in the velocity update [34].

Genetic algorithm is also a heuristic based algorithm. Unlike other optimisation algorithms, the genetic algorithm does not use the points in the set of the variables neither the values of the objective function. Each point in the set of variables is mapped onto a chromosome composed of L symbols from a predefined alphabet such as the binary alphabet $\{0, 1\}$. This mapping is called the encoding. The value of the objective function corresponding to a chromosome is called the fitness. The process of selecting

the alphabet, the chromosome length L as well as the encoding is known to be the representation scheme. Throughout the genetic algorithm, selection, crossover and mutation operations are used. Selection is a process in which a mating pool composed of N chromosomes chosen from the most recent population is created. Crossover is defined as the process in which a pair of chromosomes known as the parent chromosomes exchange symbols starting at a predefined position and for a predefined number of symbols to give rise to two offspring chromosomes that will replace the parent chromosomes in the mating pool. Mutation is defined as the process of randomly changing the symbols of each chromosome in the mating pool. In brief, the genetic algorithm starts by randomly selecting a population of N chromosomes along with their fitness values and the chromosome with the optimum fitness value is kept as the best chromosome. A mating pool is then formed by N chromosomes selected from the population. Crossover and mutation processes are applied, a new population is obtained and the best chromosome is updated. This process repeats until the stopping condition is reached [34][35][36].

Ant colony optimisation algorithm imitates the ants' behaviour. Ants start to search randomly for food leaving a pheromone on their way. When other members of the colony need to choose their path, they will choose the one with the highest pheromone level since this will correspond to the most visited track and thus this path is assumed to be the shortest path leading to food. This pheromone will evaporate with time, thus the path that is not frequently visited by ants will be less favourable to be followed later. This kind of communication and cooperation is imitated to form the basis of the ant colony optimisation algorithm. In the ant colony optimisation algorithm, “ m ” artificial ants are randomly positioned. Each ant then moves from position r to a new position s based on a state transition rule. Each time an ant arrives at a new position, it modifies the pheromone based on a local updating rule. The local update lowers the pheromone on the visited edge so that it will become less desirable for other ants and thus ants will not converge to the same path [37].

The last heuristic based algorithm discussed in this chapter is Hooke and Jeeves. Hooke and Jeeves is a pattern search algorithm based on two types of moves. The first move is an exploratory move while the second is a pattern move where a successful exploratory move is followed by a pattern move [38].

The choice of the best optimisation algorithm is problem dependent. Thus, one cannot judge any algorithm in general. Some algorithms are suitable for certain optimisation problems and cannot converge to the optimal solution for other problems. In some cases, the algorithms may converge to a sub-optimal solution. Table 3.1 presents a brief comparison of the optimisation algorithms presented in this section.

Technique	First Derivative	Second Derivative	Advantages	Disadvantages
Steepest Descent	YES	NO	Simple, Low Memory storage	May not converge
Newton's Method	YES	YES	Better than steepest descent (faster convergence)	May not converge, Requires the inverse of the Hessian matrix at each iteration
Quasi-Newton	YES	NO (Approximated)	Simpler than Newton's Method	High memory storage
Conjugate Direction Methods	YES	NO	Intermediate between Steepest descent and Newton's, Little memory	Slow (slower than Newton and Quasi-Newton)
Nelder-Mead Simplex	NO	NO	Simple to implement	Slow convergence
Simulated Annealing	NO	NO	Guaranteed convergence after sufficiently large number of iterations	Parameters' Choice, Computation time
Particle Swarm Optimisation	NO	NO	Simple and easy to implement, Computationally efficient	Applicable to specific types of problems
Genetic Algorithm	NO	NO	Simple and easy to implement	More computation time compared to PSO (slow) Convergence is not guaranteed
Ant Colony Optimisation	NO	NO	Guaranteed convergence	Convergence time is uncertain, Difficult theoretical analysis
Hooke and Jeeves Algorithm	NO	NO	Simple and easy to implement	Slow convergence rate, May not converge

Table 3.1: Optimisation algorithms Comparison

3.3 Cost Functions Derivation and Optimisation

In order to find the best location of the base stations in an urban environment (city), the authors in [39] optimised the cost function defined as the summation of the square values of the difference between the power level and a threshold power level for receivers' positions below the threshold level and zero for positions with power levels higher than the threshold. The power levels are acquired based on an empirical channel model. The optimisation algorithm used is the simulated annealing algorithm. The initial temperature was chosen to be high enough so that the base stations can move from one street to another. The temperature is then lowered in a way that the base stations move within one street. Simulations showed that simulated annealing is suitable for locating base stations in microcells. One can clearly notice that the choice of optimisation algorithm parameters is very critical. For example, if the initial temperature is not correctly chosen, the algorithm may not converge to the right optimal base stations' positions.

The authors in [30][31][40] and [41] presented one of the various ways to find the optimal base stations' locations for indoor environments. The purpose is to get the highest signal level at all possible receivers' positions. Thus the cost function is defined to be the summation of these signal levels obtained from a neural network multiplied by priority weights w selected depending on the signal level value so that receivers' positions with the lowest signal level greatly affect the value of the cost function and their number can be lowered. To transform the maximisation problem into a minimisation problem a minus sign is added to the cost function that becomes:

$$f_i = - \sum_{i=1}^N \sum_{j=1}^M S_i(x_j, y_j) w(S_i(x_j, y_j)) \quad (3.1)$$

where M is the number of possible receivers' positions, N is the number of base stations, $S_i(x_j, y_j)$ is the signal level at a receiving point with coordinates (x_j, y_j) from the base station at position i and w its corresponding weight defined to be:

$$w_j = \begin{cases} 1 & S_i(x_j, y_j) > -60dBm \\ 10 & -60 \geq S_i(x_j, y_j) \geq -72dBm \\ 100 & S_i(x_j, y_j) < -72dBm \end{cases} \quad (3.2)$$

The -72 dBm is the threshold value of the signal coverage. Note that the cost function should be in terms of the base stations' positions thus the double summation is confusing and it would better to be a single summation over the receivers' locations.

To get the optimal base station position, the above cost function was minimised in [30] and [31] using particle swarm optimisation. The particle swarm optimisation resulted in better performance compared to the Simplex algorithm and Powell's conjugate method in terms of accuracy and simulation time. In [40] and [41], the ant colony optimisation algorithm was used. The algorithm was shown to converge to an optimal base station's position that provides the best coverage for receivers. This optimal location closely matched that obtained using the genetic algorithm and particle swarm optimisation. However, in terms of convergence rate, the ant colony optimisation required much more time to reach the best base station's position compared to that required for the genetic algorithm and particle swarm optimisation.

In [42], the optimal base station's position was found by maximising the field strength over all possible receivers' positions using the genetic algorithm. The field strengths were estimated via an image based ray tracing model. Simulation showed that the genetic algorithm was effective in finding the best base station's position.

The authors in [43], [7] and [44] used the path loss based on empirical model to develop the cost function. This cost function is composed of three parts. The first part is the weighted average of the path loss. The minimisation of this part will ensure that the path loss at most receivers' locations is minimal. When multiple base stations are serving the environment, the path loss at a given receiver's position is selected to be the minimal path loss achieved from the different base stations. In other words, each receiver is assumed to be served by the base station providing the highest received signal strength. The other two parts, f_1 and f_2 , deal with receivers' positions with a path loss higher than a given threshold value. f_1 deals with the average path loss of these receivers' positions while f_2 deals with the worst receiver so that it has satisfactory service. The cost function as defined in [7] and [44] is thus as follows:

$$f = \frac{1}{N} \sum_{i=1}^N w_i \min_{j=1, \dots, M} (PL_{ij}) + \alpha f_1 + (1 - \alpha) f_2 \quad (3.3)$$

$$f_1 = \frac{1}{N} \sum_{i=1}^N w_i p_i D_i \quad (3.4)$$

$$f_2 = \max_{i=1, \dots, N} w_i p_i D_i \quad (3.5)$$

$$D_i = \max \left[0, \min_{j=1, \dots, M} (PL_{ij} - t) \right] \quad (3.6)$$

where PL_{ij} is the path loss at the i^{th} receiver served by the j^{th} base station, N is the number of receivers, M is the number of base stations, α is a trade-off factor to specify whether f_1 or f_2 should have higher influence on the cost function, w_i is a relative priority weight, p_i is a penalty factor and t is a threshold value of the acceptable signal. On the other hand, the cost function in [43] slightly differs from that defined in [7] and [44]. In [43], the trade-off factor multiplies both the weighted path loss average as well as f_1 . In addition, in the cost function of [43], even if the worst position has a path loss lower than the threshold, its value is added to the cost function calculation thus f_2 becomes as follows:

$$f_2 = \max_{i=1, \dots, N} w_i \left[\min_{j=1, \dots, M} (PL_{ij}) + p_i D_i \right] \quad (3.7)$$

The cost function in [43] is optimised using the Hooke and Jeeves technique, quasi-Newton (BFGS), as well as conjugate gradient methods. After a series of simulations for single and multiple transmitter cases, the authors recommended the use of Hooke and Jeeves and conjugate gradient method. This same cost function is optimised using seven optimisation techniques in [7] and [44]. These optimisation techniques are: steepest descent, BFGS method, simplex, Hooke and Jeeves, Rosenbrock, simulated annealing and genetic algorithm. To test these methods, two environments were simulated. The first is served by one base station and the second is served by three base stations. All the optimisation techniques with the exception of steepest descent converged to the optimal base station's position in the first environment. The fastest technique was Hooke and Jeeves whereas the slowest technique was BFGS method. As for the second environment, only Hooke and Jeeves, simulated annealing and genetic algorithm converged to the optimal position of the three base stations. The fastest algorithm was simulated annealing and the slowest was genetic algorithm. Note that the initial position of the base stations was randomly selected. A better initial position may reduce the simulation time especially for

simulated annealing and genetic algorithm. On the other hand, in the case of a single base station, the initial position in [43] was set to be the position that minimises the sum of the weighted squared Euclidian distance between the base station and each receiver. In the case of multiple base stations, the space is iteratively split into M regions depending on the weights of the receivers' positions and then each base station is located within one of the regions based on the same criterion described for the single base station scenario. The choice of the initial base station's position improved the results in terms of simulation time and convergence of the optimisation algorithms used. In addition, in order to reduce the simulation time, the grid size was varied throughout the simulation. A large grid size is used first in order to lower the computations while evaluating the cost function. Thus, the optimisation algorithms will approach the optimal solution in a lower computation time. The grid size is then decreased in order to improve the optimal base stations' positions.

In [45], the cost function is defined in terms of quality-of-service where the QoS is the percentage of time during which good service is preserved. The outage probability is then expressed as follows:

$$P_{out}(x, X_{BS}) = 1 - QoS(x, X_{BS}) \quad (3.8)$$

where x is the receiver's position and $X_{BS} = [X_1, X_2, \dots, X_M]$ is the vector of positions of the M base stations distributed in the environment. This outage probability should be maintained at a minimum for all receivers served at a predefined area S . The objective function is then the weighted spatial average:

$$f(X_{BS}) = \int_S P_{out}(x, X_{BS}) p(x) dA \quad (3.9)$$

$p(x)$ is the probability density function of the traffic at location x and it was assumed to follow a uniform distribution. The outage probability is found depending on the environment. The cost function is then minimised using the simplex and Powell's conjugate algorithms. It was shown that the simplex algorithm reached the same or better optimal positions of the base stations and in a faster way compared to the Powell's conjugate algorithm.

In addition, the cost function can be based on the coverage percentage as in [46] where the authors defined the cost function to be the number of receivers' positions with power greater than a predefined threshold value divided by the number of all

receivers' positions. The cost function is then maximised using the genetic algorithm. It was noticed that the genetic algorithm is effective in the optimisation of base stations' locations. The same cost function was used in [14], however the optimisation technique adopted was the Nelder-Mead simplex algorithm and it was also found to be an efficient algorithm for this kind of optimisation problem.

The cost function in [47] was expressed in terms of the size of the uncovered area and the size of the interference area. N base stations operating at the same frequency were assumed to serve the environment that is divided into a rectangular grid. Omni-directional and adaptive antennas were used. A mobile is served by the base station with the highest signal strength as long as this signal strength is above a predefined threshold value. Due to the presence of multiple base stations, co-channel interference may affect the communication between the mobile device and the base station. This interference strength is defined to be the summation of the signal strength from all base stations operating in the environment other than that serving the mobile device. The signal-to-interference ratio (SIR) is then the ratio of the signal strength of the base station serving the mobile and the interference strength. As long as the SIR is above a given threshold value, communication is maintained. Thus the environment can now be divided into four regions. The first is the cell area in which the signal strength is above the threshold value. The second is the covered area in which the signal strength and the SIR are above their threshold values. The interference area is the third area and it is the area where the signal strength is above the threshold value but the SIR is below its threshold value. The last area is the uncovered area where the signal strength is less than the threshold value. The location and power of the base stations should be chosen in a way that minimises the uncovered and the interference areas. The cost function is thus:

$$f(x_1, y_1, p_1, \dots, x_N, y_N, p_N) = \alpha U + (1 - \alpha)I \quad (3.10)$$

where U and I are the size of the uncovered area and the size of the interference area respectively and α is a priority weight between 0 and 1. Note that to reduce the uncovered area, the transmitted power should be increased but this will increase the interference area. On the other hand, the interference area can be reduced by moving the base stations away from each other but this will increase the uncovered area. In order to minimise this cost function, the variables were considered to be either over a continuous space or over a discrete space where the base stations can be placed at one point in the

rectangular grid and the power can take a value from a finite set. For the continuous space, the optimisation techniques used were the steepest descent and the Nelder-Mead simplex algorithm. For the discrete case, a neural network was used. The optimisation of the cost function was done twice, once with respect to the base stations' positions and once with respect to the transmitted power. Near optimal solutions were obtained, however in some cases steepest descent failed to converge.

3.4 Optimal Base Stations' Positions without a Cost Function

The authors in [48] did not use the well-known optimisation techniques instead they implemented an algorithm using a serialable L-system. There is not a cost function in this implementation. It is supposed first that one base station serves the environment. The area is split into two sub-areas in the vertical and horizontal directions. The received power is then calculated at the farthest point from the base station within each sub-area and these values are stored. The process repeats until an edge of the sub-areas is less than a predefined length. If the power of any test point is less than a threshold value, the base stations should be moved to another place and the calculation starts again. If the current number of base stations is not able to cover all test points then an additional base station should be placed in the environment. Note that even if all test points receive a power above the predefined threshold this does not mean that this is the optimal position. The optimal position and the positioning of additional base stations are based on calculations of averages and averages' differences of the power at the test points.

In [49], the optimal base stations' positions are found without a cost function definition too. It is first assumed that all base stations are active and all mobile devices are required to establish a connection. Each mobile device is connected to the base station with the highest SIR above a threshold value on the forward link. When all mobile devices are connected, the base station with the lowest number of mobile devices is disabled. The mobiles are then reconnected to the new set of base stations. The process repeats as long as all mobiles are able to establish a connection. The same process is repeated for the reverse link. The resulting number of base stations is not yet considered the minimum number. The algorithm continues by searching if the system is able to serve the receivers with all possible configurations having one base station less

than the obtained minimum. If this was possible then one base station is removed and the process repeats again otherwise the previously obtained number of base stations is considered the optimal value. From all the possible configurations composed of the minimum number of base stations, the one with the highest average forward link SIR value is chosen to be the optimal configuration. The authors considered that this algorithm is an effective algorithm ignoring the fact that channel measurements are done for every possible configuration throughout the algorithm simulation instead of simply using ray tracing or even a statistical channel model. In addition, the way the interference levels are found is not described, keeping in mind that the SIR values are the core of the algorithm.

3.5 Conclusions

In order to find the optimal base stations configuration, mainly their locations, amount of emitted power and/or minimal required number, different forms of cost functions can be defined based on the performance measures of interest. This chapter presented some simple cost functions like the weighted summation of signal levels and other more sophisticated forms that look into more than one performance measure. The measures used to define the various cost functions are the field strength values, the path loss values, the outage probability, the coverage percentage, the uncovered area as well as the interference area.

On the other hand, the selection of the channel model affects the accuracy of the obtained performance measures which in turn affects the cost function values and the optimal solution. Appropriate selection of the channel model is therefore required to get a realistic optimal solution.

Due to the nature of the cost function for this type of optimisation problem, gradient based optimisation techniques are not widely used as they require derivatives. Thus, whenever they are used, the derivatives are numerically approximated. Instead, heuristic based optimisation techniques are used and they led to accurate results within an acceptable simulation time. Note that when the variables of the cost function are selected from a limited predefined set or in other words, when the number of cost function values is limited, one can use brute force optimisation approach. In this case

the exact optimal solution is obtained whereas if an optimisation algorithm is used, the solution might be a sub-optimal solution.

Although the literature presents some cost function built based on a combination of measures, the time dispersion parameters are never considered despite their effect especially on high speed wireless communication systems. Sufficient signal level reaching a certain receiver's position does not mean the receiver will enjoy service. As discussed in chapter 2, if the rms delay spread is high compared to the symbol period, intersymbol interference occurs increasing the error rate and consequently deteriorating the service. Therefore, defining a cost function based on the signal level measures alone is not enough and the time dispersion parameters must be included. Chapter 6 will present different forms of cost functions defined based on both the path loss and the rms delay spread values.

Chapter 4: Indoor Environments Setup and Ray Tracing Software Parameters

4.1 Introduction

Finding the optimal base stations' positions requires knowledge of the channel characteristics. Different channel modelling techniques were described in chapter 2. Empirical channel models can be easily implemented but lack accuracy, whereas deterministic channel models produce more accurate results at the cost of complex implementation in terms of the amount of memory required and the simulation time. The selection of the appropriate technique depends on the environment type. The target of this research is dynamic indoor environments where the channel characteristics depend on individual environments, thus a deterministic model should be selected. Consequently, a sophisticated 2D ray tracing program previously developed at the University of Bath [3] [4] has been selected.

The software requires the detailed 2D map of the environment including the furniture along with the permittivity and conductivity of the materials available in the environment. It also requires some transmitter's parameters, mainly the frequency and field polarisation. In addition, a cut-off power level below which rays are not traced must be specified. The software generates the field strength, the ratio of the power received and the transmitted power, the first delay, the mean excess delay, the root-mean-square (rms) delay spread and the coherence bandwidth.

In this chapter, the indoor environment that is used as the test environment throughout this work will be described in addition to the ray tracing software parameters selected. The field strength values generated by the software will be compared with measurements done in the environment. Furthermore, the fact that the software ignores diffraction will be discussed.

4.2 Environment 2D Map and Its Representation using the Ray Tracing Software

In order to examine the concepts proposed in this research, a 13.45 m \times 23.7 m home in Lebanon was selected. Figure 4.1 shows the 2D map of the environment and

the furniture distribution. The ray tracing software has a drawing tool where the 2D map of the indoor environment is plotted based on equal dimension rectangular cells. Each cell represents a material type with predefined permittivity and conductivity. The selection of the cell size depends on the tiniest object that needs to be represented in the environment map. Smaller cell size helps obtaining more accurate environment mapping but increases the ray tracing simulation time as every ray is traced as it goes from one cell to another until its power falls below a predefined threshold value. The cell size used to represent the indoor environment shown in Figure 4.1 is $5\text{ cm} \times 5\text{ cm}$. The resulting map is shown in Figure 4.2 where each colour represents a material type.

This environment will be considered in different circumstances. In the first scenario, the environment will be considered empty without furniture. It will then be considered furnished with all windows and doors closed. All the windows and doors except the main door will be opened in the third scenario. Finally, people will be added to the environment with all doors and windows closed. Note that people are shown in green in the ray tracing software map (Figure 4.2).

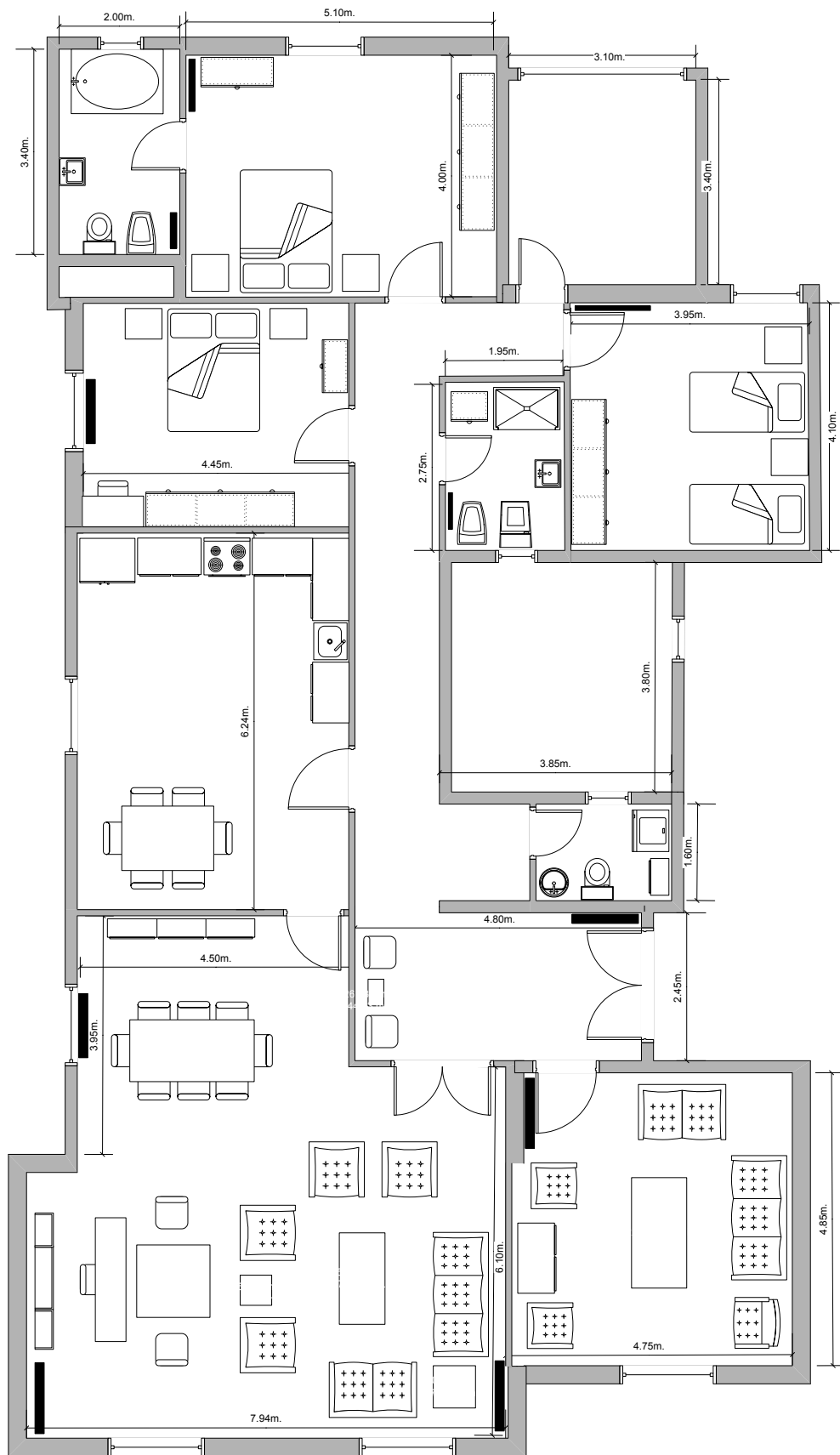


Figure 4.1: Environment 2D map

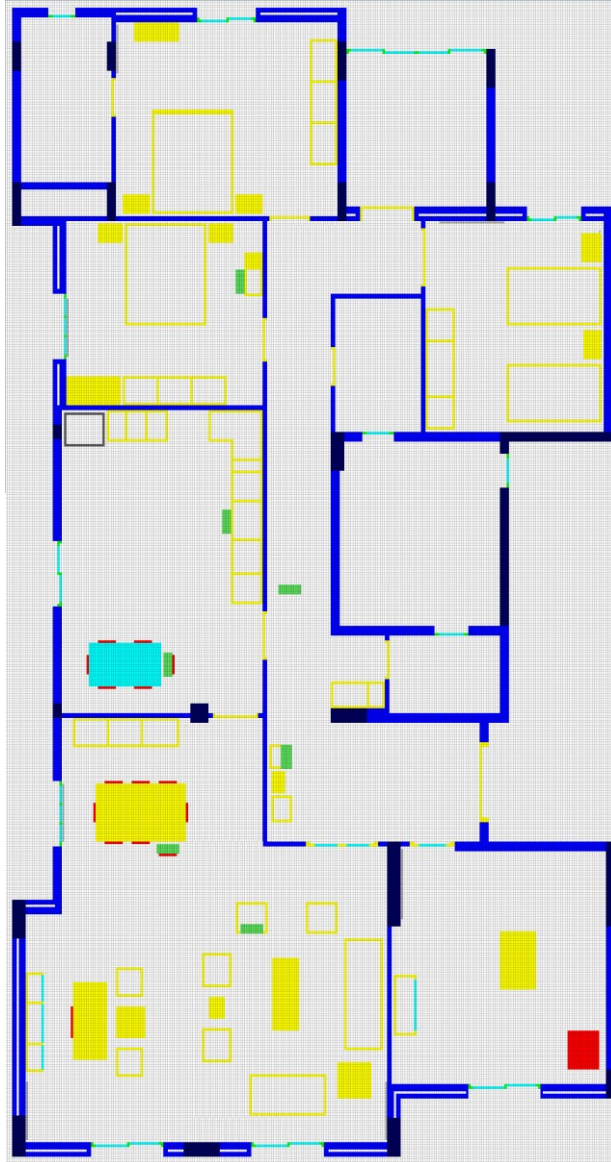


Figure 4.2: Environment 2D map as viewed in the ray tracing drawing tool

4.3 Permittivity and Conductivity Values

The walls of the environment consist of hollow blocks as well as concrete. Doors, windows and some furniture are made of wood and glass. The environment also contains chairs covered with cotton as well as aluminium heaters and a stainless steel fridge. In addition, people are placed in the environment. Table 4.1 shows the permittivity and conductivity of the materials used to model the environment.

Material Type	Relative Permittivity	Conductivity (S/m)
Air [50]	1	0
Hollow Blocks [50][51]	2.3	0.005
Concrete [59]	4.5	0.0066
Wood [51]	3	0.05
Glass [51]	4.56	0.001
Cotton [52]	5.34	0.0406
Aluminium [53]	1	3.5×10^7
Stainless Steel [53]	1	1.45×10^6
People [54]	80	1.2

Table 4.1: Materials permittivity and conductivity values

4.4 Base Station's Parameters Selection and Their Effect on The Field Strength

In addition to the cell size, the cut-off power level value below which a ray is not traced anymore must be specified. Furthermore, the frequency of the emitted signal, the field polarisation, as well as the transmitter's position must be specified. The frequency selection depends on the application. It is selected to be 2.4 GHz throughout this work while the polarisation is set to be parallel (the electric field is normal to the reflecting surface). As for the cut-off power level, it is selected to be -90 dB. Changing these parameters will result in different channel characteristics. The effect of the cut off power level and polarisation selection on the field strength is shown in sections 4.4.1 and 4.4.2.

As for the transmitter's location, it is specified by selecting the Cartesian coordinates of the desired position in the environment. In the later chapters, the optimal base station's position must be found, thus the base station is located at different places throughout the environment. Those locations are selected based on a $1.5 \text{ m} \times 1.5 \text{ m}$ grid. It will be shown in chapter 8 that a limited movement of the base station does not highly affect the overall statistics of the channel, therefore if the base station is located anywhere within the $1.5 \text{ m} \times 1.5 \text{ m}$ grid, similar coverage will be achieved. Figure 4.3

shows the Cartesian coordinates of some of the possible transmitter's locations that will appear in the tables summarising the optimal locations in later chapters. Note that some transmitter's locations that falls inside bathrooms or outside the environment are excluded and are shown as red dots in Figure 4.3. In addition, when furniture is added to the environment, some of the locations that used to be possible in the empty environment are not considered due to the presence of objects. These locations also appear as red dots in Figure 4.3. However, if moving the base station within 20 centimetres around the centre of the grid cell brings the position out of the object, the location is not excluded. These locations are circled in red in Figure 4.3.

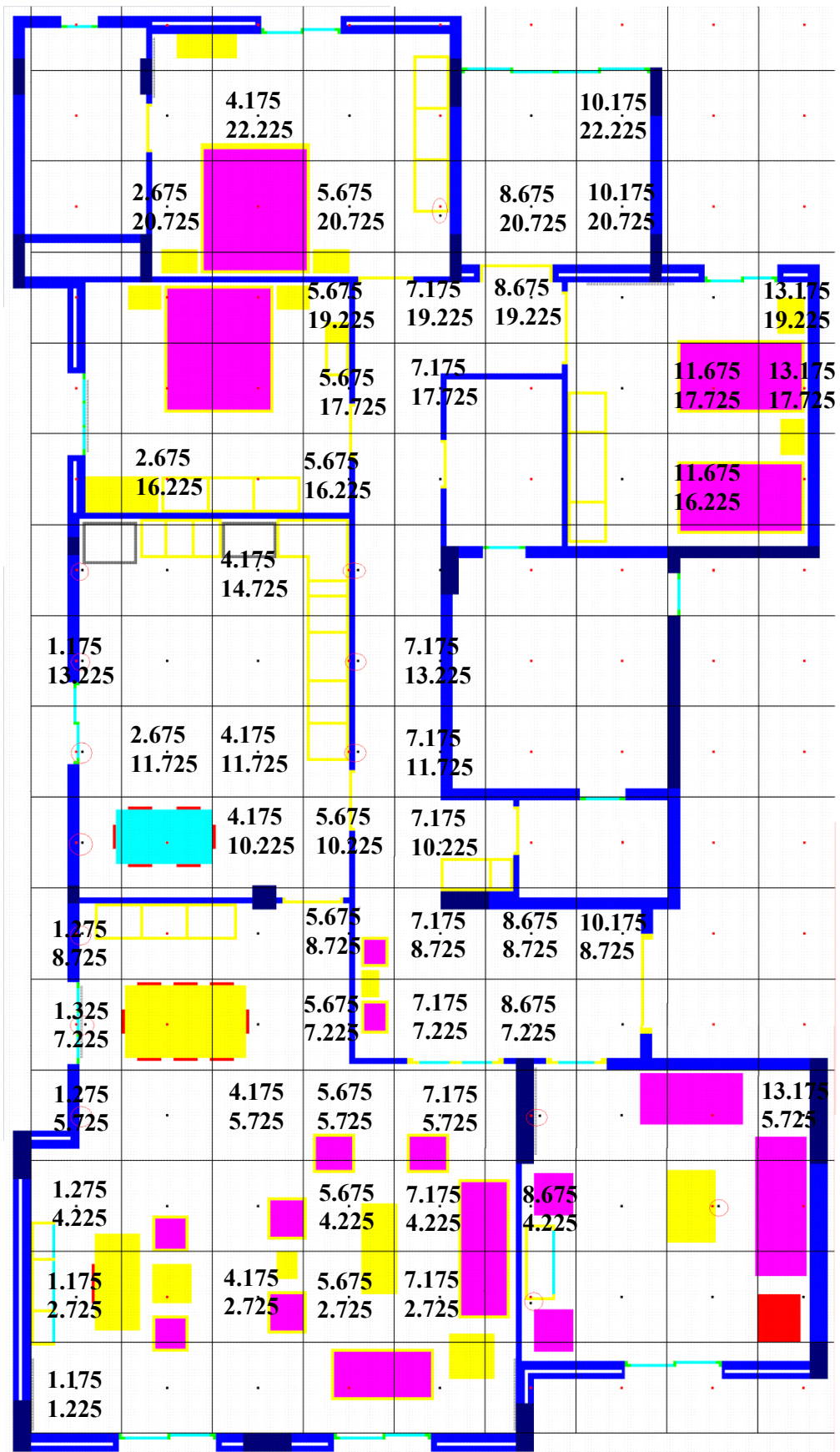


Figure 4.3: Cartesian coordinates of some of the possible transmitter's locations

4.4.1 Cut-Off Power Threshold Change

Rays are launched and traced as they propagate throughout the environment. Rays may bounce back and forth depending on the material they are facing. In reality, this process will continue infinitely. However, in practice, there must be a point where the ray power must be considered negligible and its value does not highly affect the field reconstruction process throughout the environment. In other words, the ray tracing software must stop tracing the rays when their power falls below a predefined threshold. The further the rays are traced, the more precise the simulation results are.

Figure 4.4 shows the field strength across the previously defined indoor environment for a random transmitter position and two different cut-off power levels: -60 and -90 dB. As it can be seen, the highest field strength is found near the base station. The further the user is from the base station, the weaker the field strength is. On the other hand, a lower cut-off value means rays are traced further and this allow a ray to reach a longer distance thus more rays will contribute in the total field strength at a given position in the environment. This can be clearly noticed in Figure 4.4 where the field strength values in the environment are higher for the -90 dB cut-off value. Figure 4.5 shows the difference between the field strength values of the -60 dB and -90 dB cut-off power levels. Lowering the cut-off power level leads to more accurate results but it increases the simulation time. For example, the simulation time was approximately three times more when using a cut-off of -90 dB instead of -60 dB. Decreasing the cut-off value further has hardly changed the field strength values over the environment thus the -90 dB cut-off was adopted for all the simulations done in this research. Note that the cut-off power levels are relative to the transmitted power. As the software emits a power of 15 dBm and based on the -90 dB cut-off power level, the minimum receiver's sensitivity must be -75 dBm such that, in the worst case scenario, when a single ray having a power of 90 dB below the transmitted power reaches the receiver, the receiver can detect it. Otherwise, this ray is assumed to be present based on the ray tracing software while the receiver cannot detect it. The -75 dBm is a typical sensitivity as mentioned in [55].

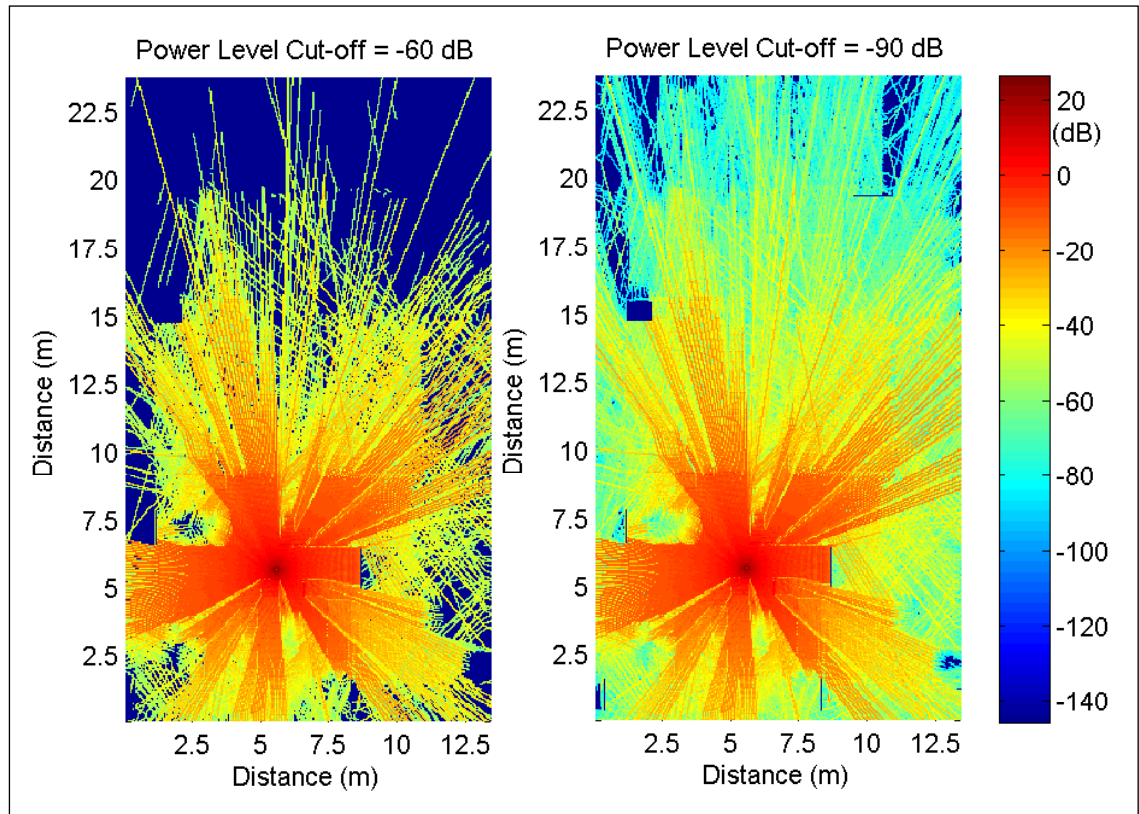


Figure 4.4: Field strength throughout the environment for two different power cut-off levels

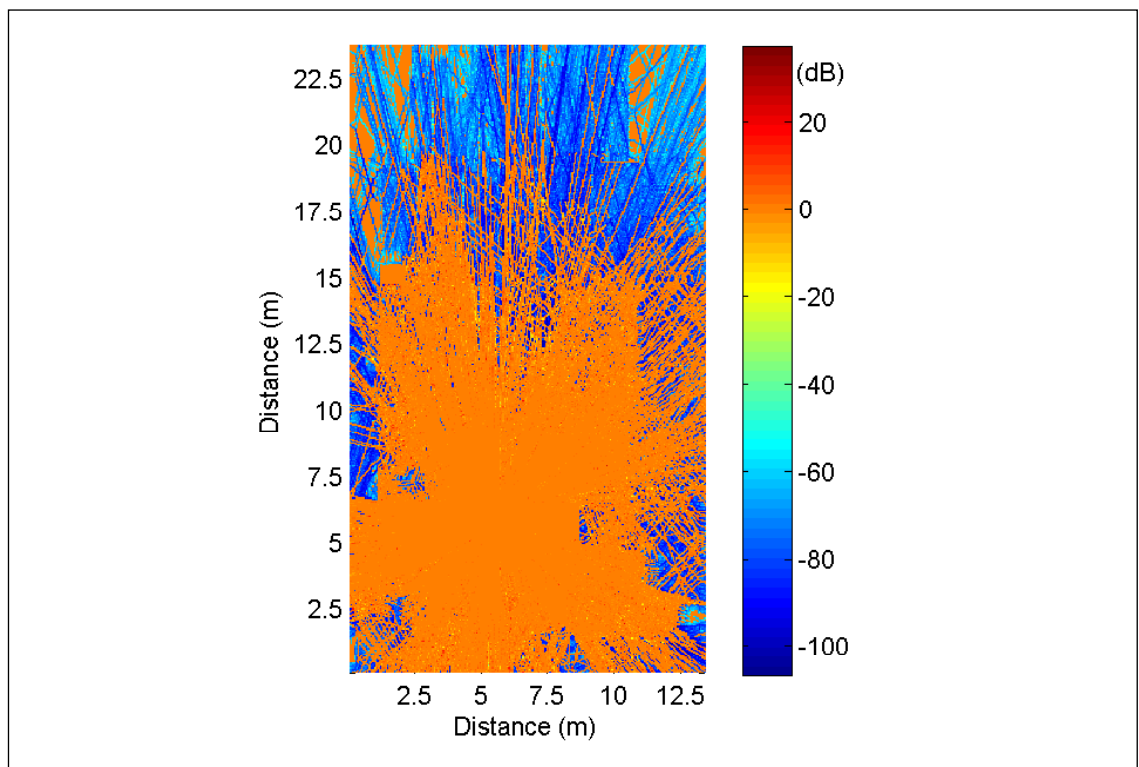


Figure 4.5: Difference in the field strength between the -60 dB and the -90 dB cut-off power levels throughout the environment

4.4.2 Polarisation Change

The field polarisation depends on the antenna used. The software allows the selection of either the parallel polarisation (the electric field is normal to the reflecting surface) or the perpendicular polarisation (the electric field is parallel to the reflecting surface). Note that the field polarisation is assumed to be preserved as it travels throughout the environment. The reflection and refraction coefficients depend on the field polarisation as explained in chapter 2. Accordingly, the field strength over the environment will vary with the polarisation change. Figure 4.6 shows the field strength over the environment for the same transmitter's position but with different polarisations (parallel or perpendicular). It can be seen that some of the locations that are far from the transmitter have higher field strength when the perpendicular polarisation is used keeping in mind that due to the 2D ray tracing model, the floor and ceiling reflections are ignored. The reflection coefficient of the parallel polarisation is always lower than that of the perpendicular polarisation [56]. Consequently, whenever any reflection occurs after the signal hits a wall at the boundary of the environment, a bigger portion of the signal is reflected back inside the environment if the perpendicular polarisation is used as opposed to the parallel polarisation. For this reason, if the perpendicular polarisation is used, the signal is more preserved inside the environment and different field strength distribution is obtained with higher signal level reaching farther locations. As the rays can add constructively or destructively some locations have higher field strength while others have lower field strength. This can be observed in Figure 4.7 which shows the difference in the field strength between the parallel and perpendicular polarisations respectively.

On the other hand, as the signal is more preserved inside the environment, the simulation time of the perpendicular polarisation will be longer than that of the parallel polarisation. In fact, the perpendicular polarisation simulation time is approximately three times more than that of the parallel polarisation although this depends on the transmitter's position and in some cases the difference can be even higher. Therefore, the parallel polarisation is mainly used. Note that the polarisation selection will not affect the general conclusions of this research and this will be discussed in chapters 5 and 7.

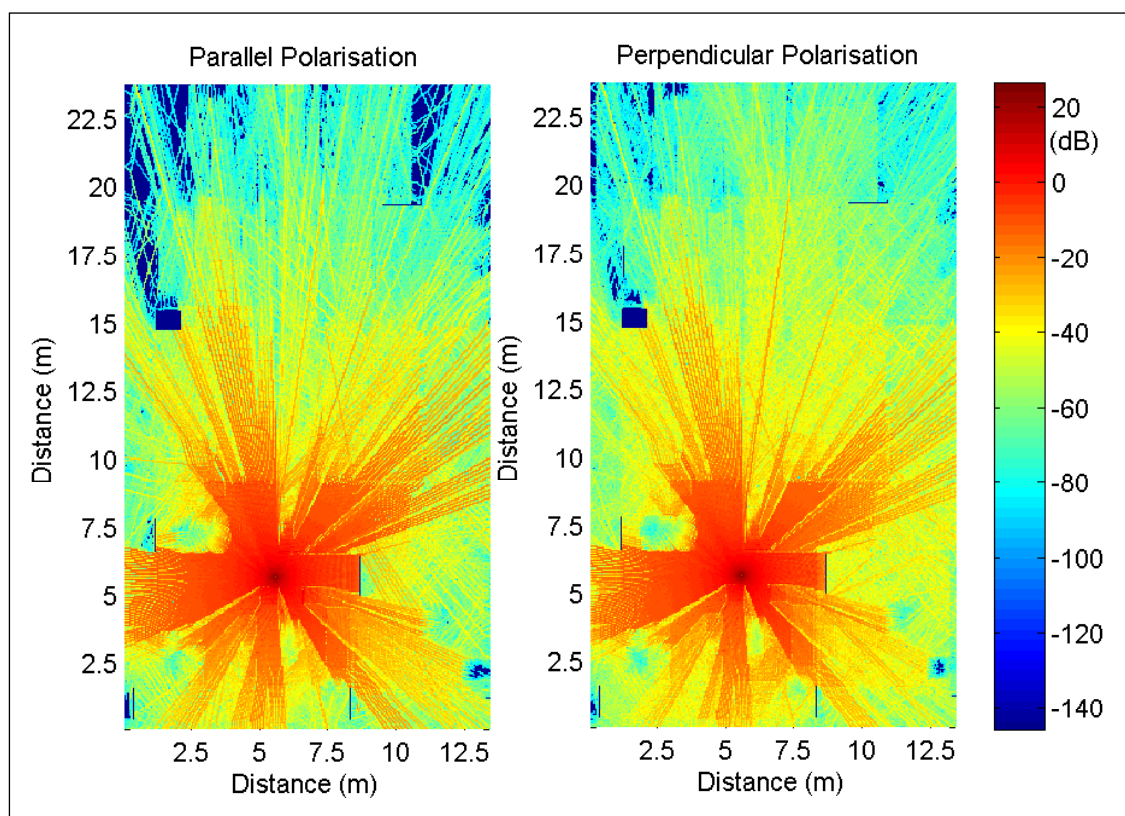


Figure 4.6: Field strength throughout the environment for parallel and perpendicular polarisations

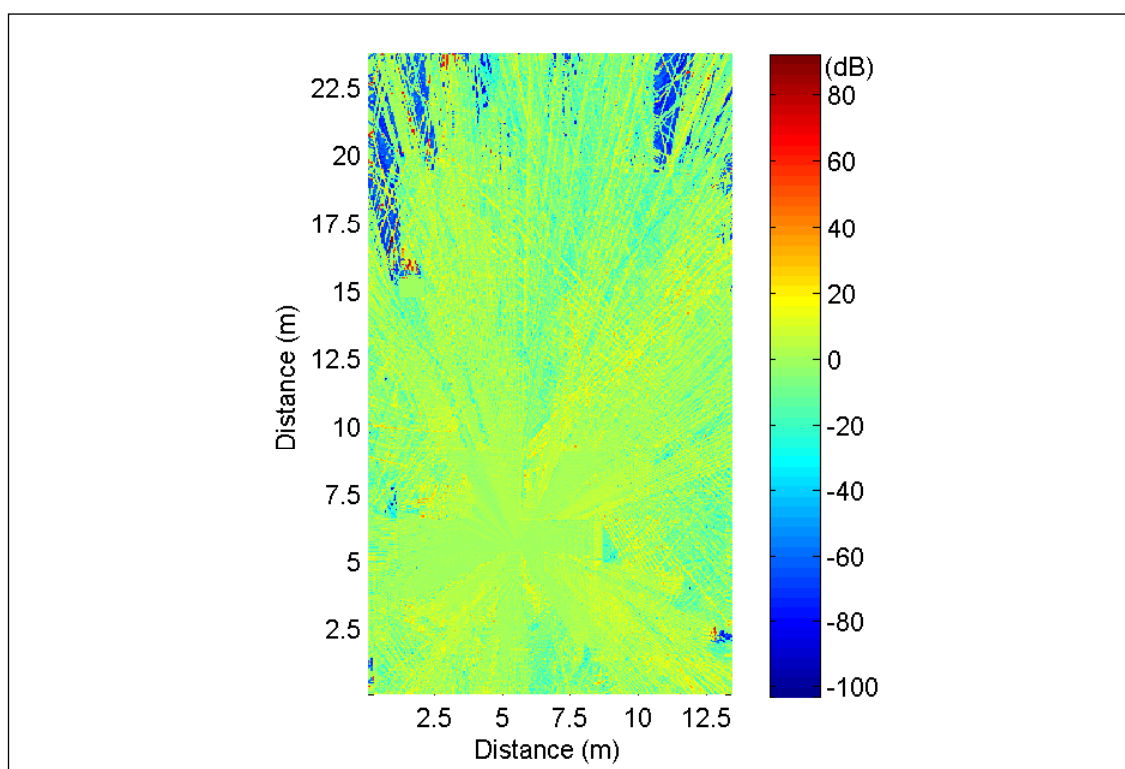


Figure 4.7: Difference in the field strength between the parallel and perpendicular polarisations throughout the environment

4.5 Ray Tracing Software Validation

In order to verify the field strength values produced by the ray tracing software, measurements were done in the environment using a WIFI analyser application when all doors and windows of the environment are closed without the presence of people. Hundred measurement points were selected throughout the environment marked in red in Figure 4.8. As for the transmitter location, it was selected to be with coordinates (7.175, 16.225) (marked in green in Figure 4.8).

The measured and simulated field strength values of the selected possible receivers' locations are plotted in Figure 4.9. The closest match was for the points 22 to 40, as for the rest of the points one can notice similar variation trends. On the other hand, Figure 4.10 shows the cumulative distribution function of the measured and simulated field strength values. The two curves are close for high field strength values whereas they are distant at low values. The reasons behind this mismatch can be due to a series of reasons, mainly, the un-modelled objects outside and inside the environment as well as the accuracy of the materials conductivity and permittivity values. As an example, some walls may contain some thin metallic bars that were not modelled. In addition, the diffraction was not taken into account during the ray tracing which add uncertainty to the simulated field strength values as opposed to the measured ones although it will be shown in the next section that diffraction can be neglected.

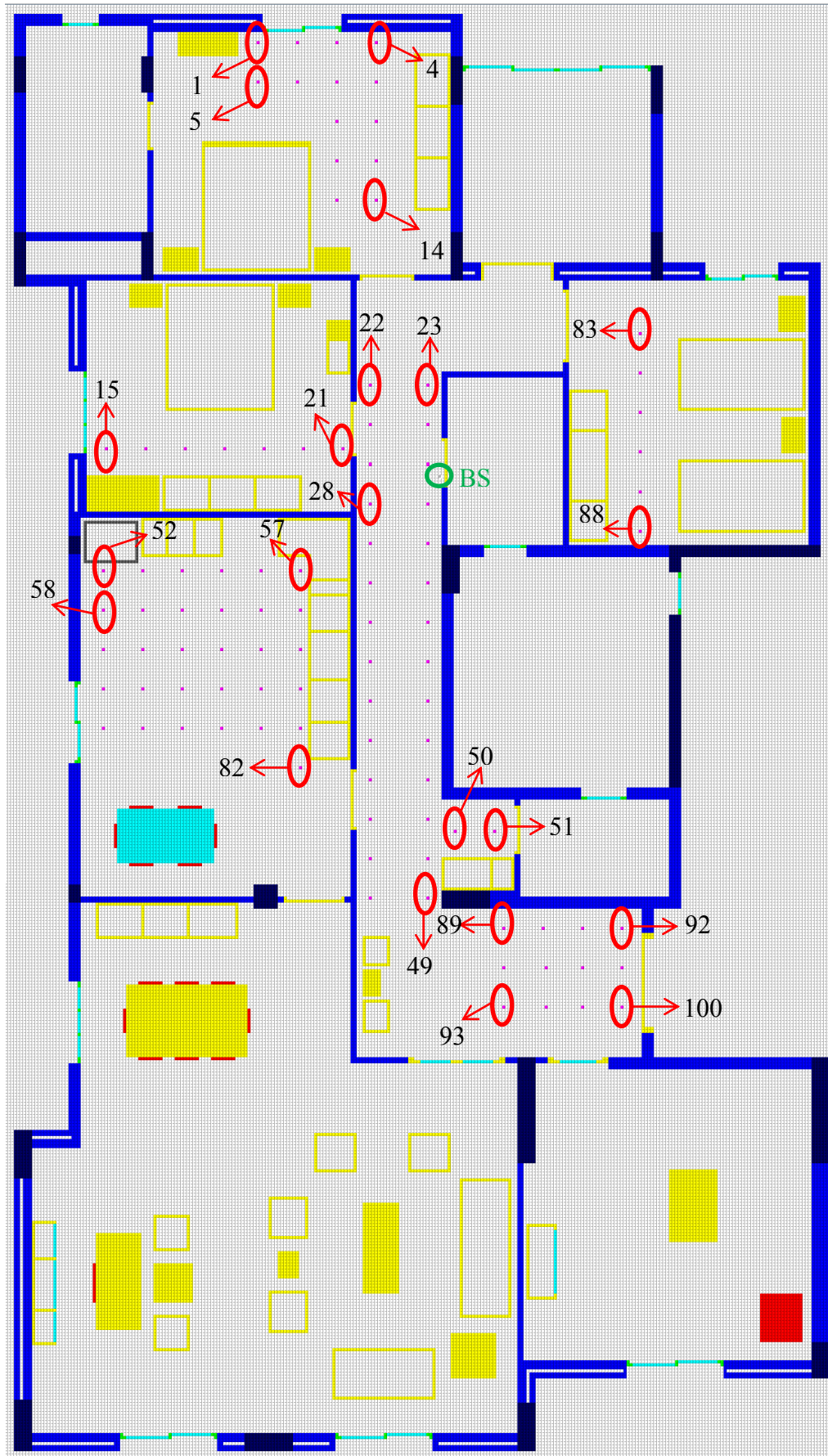


Figure 4.8: Receiver's locations where measurements were performed

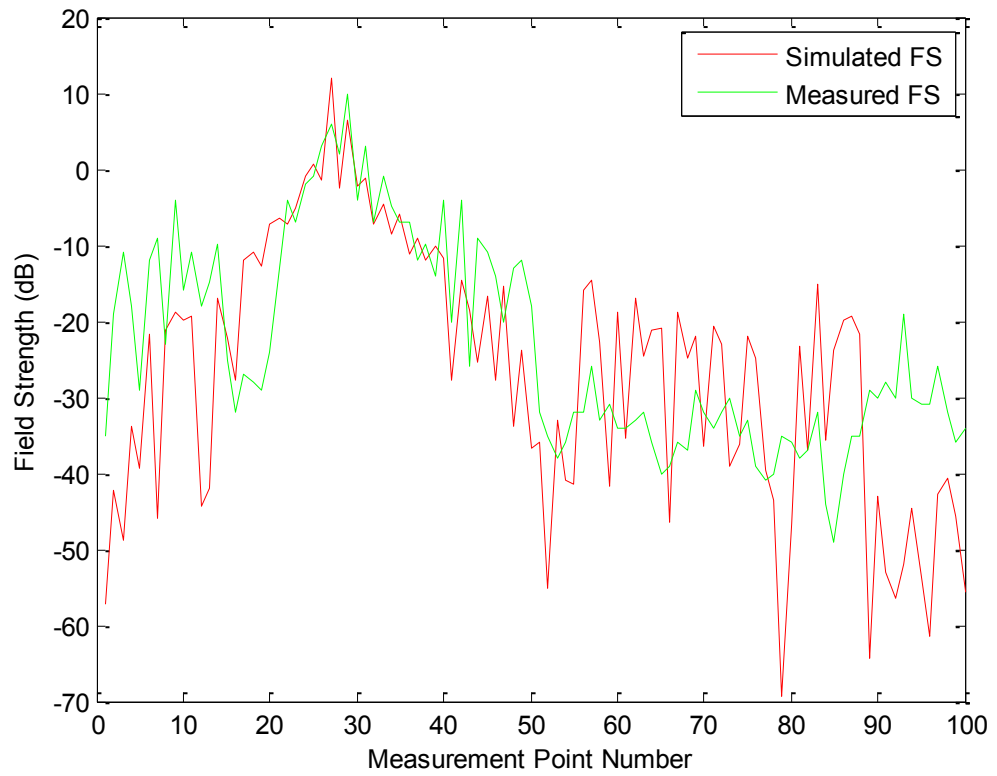


Figure 4.9: Measured and simulated field strength values over the 100 selected receiver's locations

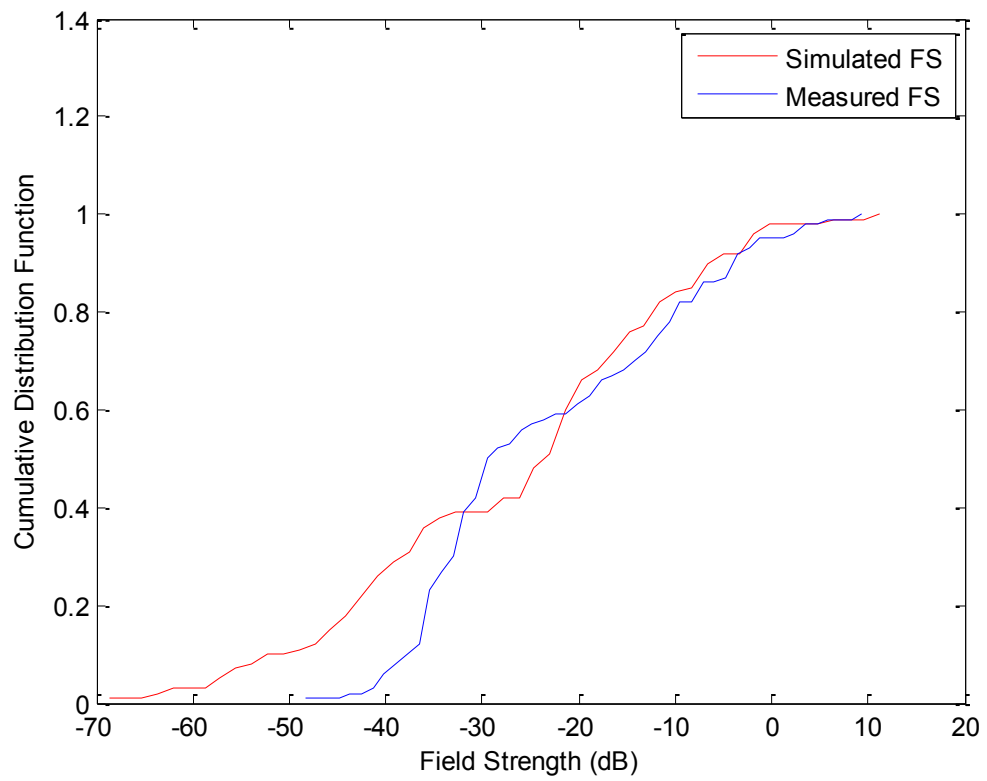


Figure 4.10: Cumulative distribution function of the measured and simulated field strength values over the 100 selected receiver's locations

4.6 The Effect of Diffraction on The Simulated Path Loss Values

The 2D ray tracing software adopted throughout this work ignores diffraction. In order to obtain an idea whether this does have a high influence on the simulated path loss values or not, a transmitter location with coordinates of (5.675, 14.725) is selected. The transmitter has direct line-of-sight with two corners where an incident ray will be diffracted. The two incident rays R_{I1} and R_{I2} are considered and four receivers' locations are selected as shown in Figure 4.11. The diffracted rays are therefore R_{D1} , R_{D2} , R_{D3} , and R_{D4} with diffraction angles 42.8° , 24.06° , 33.57° and 28.79° respectively calculated based on the geometry of the environment. The knife-edge diffraction model discussed in section 2.3.2 is used to calculate the diffraction loss. Figure 4.12 shows the diffraction loss versus the diffraction angle for each of the four considered receiver's location with d_1 being the distance between the transmitter and the diffraction edge and d_2 that between the receiver and the diffracting edge. Note that the diffraction angle depends on the incident ray angle as well as d_1 and d_2 . Given the diffraction angles of the considered diffracted rays, the corresponding diffraction losses are 29.5 dB, 27 dB, 25.2 dB and 24.6 dB for the rays R_{D1} , R_{D2} , R_{D3} , and R_{D4} . In addition, the rays travelling from the transmitter and then diffracted will encounter free space path loss too. The total losses are then 89.37 dB, 85.46 dB, 80.63 dB, 79.41 dB with the free space path loss calculated based on the equation defined in [1] as follows:

$$PL(\text{dB}) = 10 \log_{10} \left(\frac{4\pi d}{\lambda} \right)^2 \quad (4.1)$$

with λ being the wavelength and d the distance the ray traverses.

The simulated path loss values in the closed environment at the four selected receivers' locations are: 65.27 dB, 71.36 dB, 63.22 dB and 56.13 dB. Therefore, the loss of the diffracted rays is noticeably larger than that obtained when the diffraction is not taken into consideration and can be neglected. Furthermore, the fact that the fields transmitted through the obstacles are not ignored reduces the effect that the diffraction will add to the total path loss.

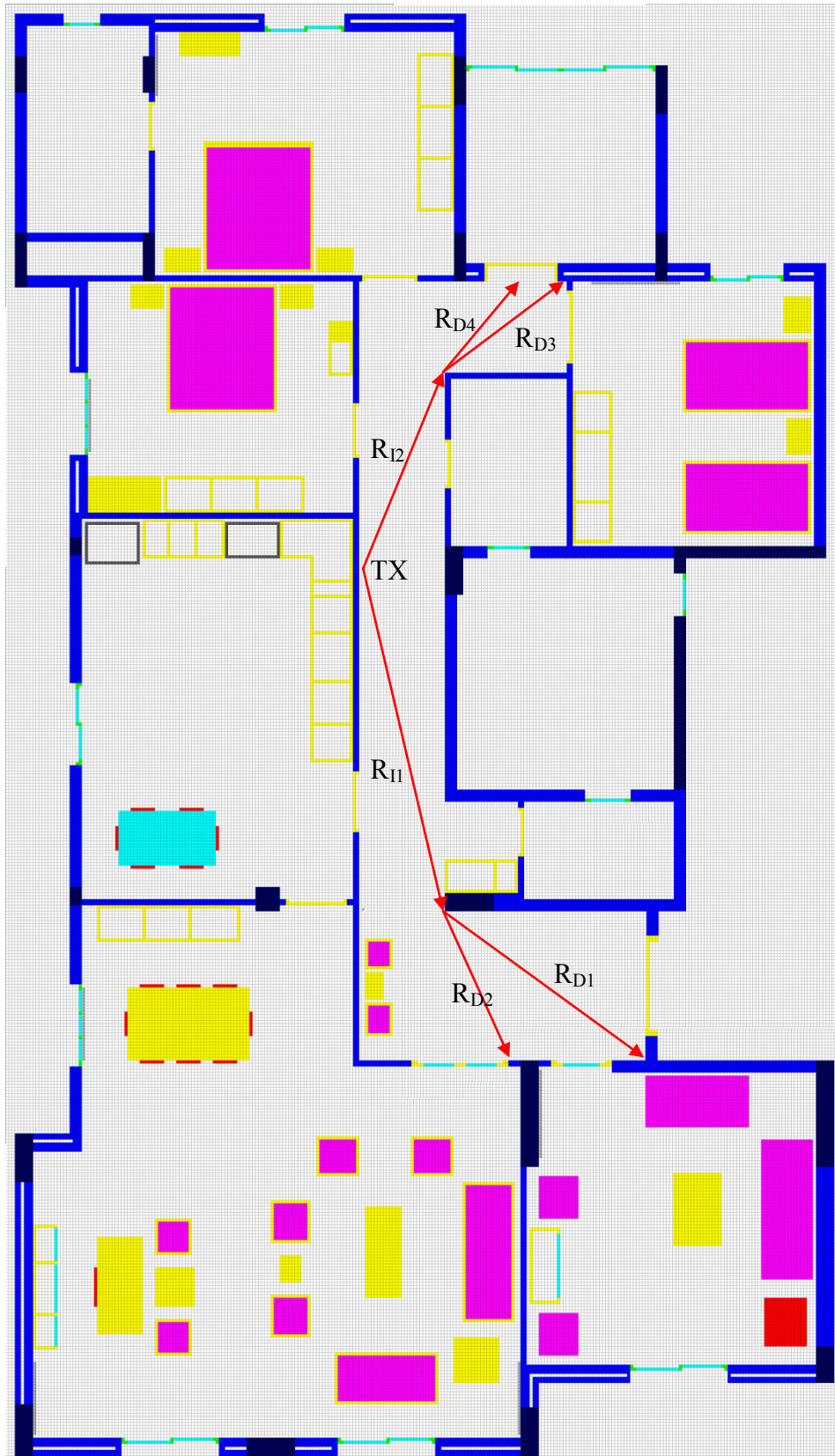


Figure 4.11: A sample of incident and diffracted rays

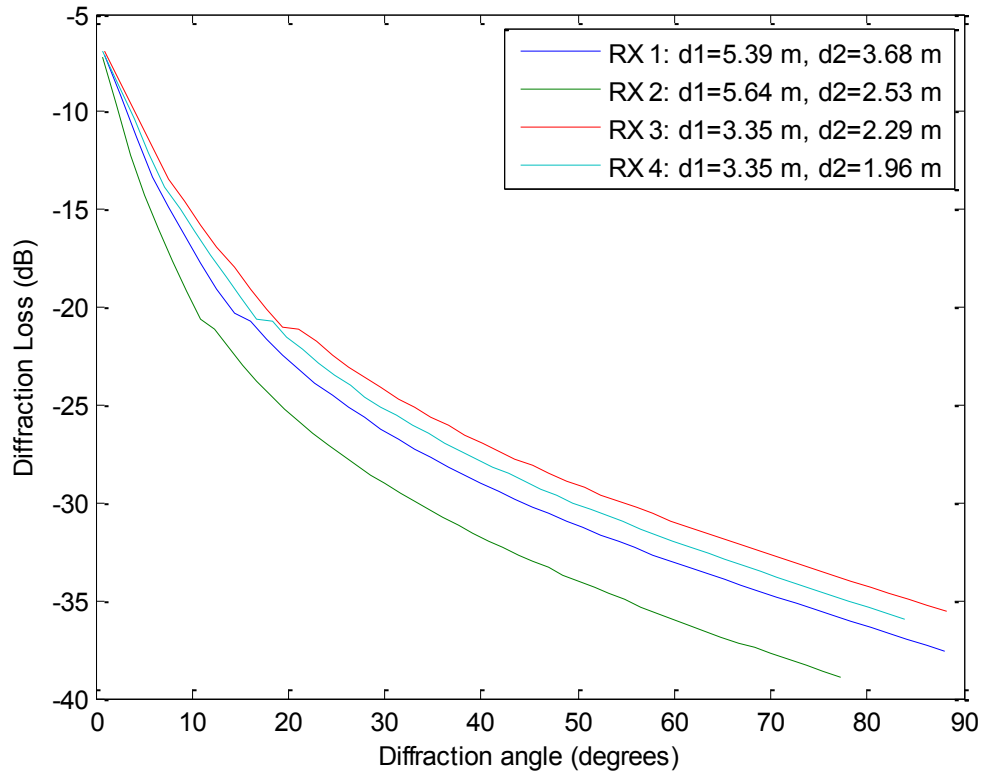


Figure 4.12: Diffraction loss versus the diffraction angle for different combinations of distances separating the transmitter and the diffracting edge (d_1) and the receiver and the diffracting edge (d_2)

4.7 Conclusions

Indoor environments channel characteristics highly depend on the features, geometry and dielectric properties of the constituent of the environment and empirical channel modelling techniques do not provide accurate results for such environments. The alternative is the use of deterministic channel modelling techniques to obtain more accurate results although those techniques are more complex.

A 2D ray tracing software was selected to get the channel characteristic of an indoor environment where walls, windows, doors and furniture were modelled and their material permittivity and conductivity were specified. The main parameters that the ray tracing software requires are the transmitter's frequency, transmitter's location, polarisation and cut-off power level in addition to the cell size used to prepare the environment 2D map. The selection of the parameters affects the channel characteristics results as well as the simulation time. The frequency selection is application dependent

while the polarisation depends on the antenna used. As for the cut-off power level value, it will reach a point where more decrement will hardly affect the field strength calculation while increasing the simulation time. The cell size selection depends on the objects' sizes to be modelled. A smaller cell size allows the representation of smaller environment's details but highly increases the simulation time.

3D ray tracing would be preferable but this will increase the simulation burden that may not be even attainable. It was shown through measurements that the 2D ray tracing used generates results that are accurate enough to illustrate the dynamic changes that may occur in an indoor environment.

Chapter 5: Optimising the Emitted Power and the Base Stations' Positions based on the Path Loss

5.1 Introduction

The mobility that wireless communication offers to users, added to the ease of installation as it does not require cabling, have increased the demand on such communication systems. Recently, most indoor environments rely on wireless communication systems. The question is where to place the base stations in order to get non-stop high quality service. With the intention of getting the optimum base stations' locations, the first step is to identify the channel characteristics and then use them to mathematically model the problem as an optimisation problem with the variables being the base stations' coordinates. The objective function can be defined in different ways and based on different channel characteristics' parameters. Chapter 3 discussed some of the approaches used in defining the objective function present in literature.

This chapter will first define a new cost function based on the path loss values. It aims at minimising the overall path loss values over the indoor environment while trying to minimise the number of receivers' locations with high path loss. Note that other cost functions built based on other channel characteristics will be defined in chapter 7. The environment previously defined in chapter 4 will be used to test the cost function in its various forms starting with it being empty. The base stations' locations will most probably be selected while preparing the electric installation of the environment when the furniture distribution is unknown. This means that it is most likely to select the base stations' locations based on an empty environment. Furniture will then be added to the environment along with some changes in order to model possible variations that may occur in any indoor environment. The changes are opening doors and windows as well as introducing people. The main purpose of introducing such changes is to check whether they have an influence on the optimal base stations' positions. As for the path loss values, they are obtained using the sophisticated ray tracing software [3][4] described in chapter 4.

After finding the optimal base station's position, the amount of emitted power is minimised. That is the minimal amount of power required to provide a predefined coverage percentage in the environment is calculated. The purpose of calculating the

least amount of power needed is to reduce the power consumption and minimise the interference with neighbour base stations. Different environment's configurations will be used and the effect of environment changes on the amount of emitted power will be discussed.

Another way of minimising the amount of emitted power is achieved by using multiple base stations [57], thus the optimal base stations' positions as well as the minimal amount of emitted power by each base station required to provide a specific coverage are found when the environment is assumed to be served by two and three base stations. This will be done for the different environment's configurations too. A summary of the results discussed in this chapter are presented in [58] and [59]. Note that when multiple base stations serve the environment, the co-channel interference was neglected due to the fact that within the 2.4 GHz range, three non-overlapping channels can be used and that is the maximum number of base stations used.

Although brute-force optimisation approach will be adopted throughout this work, the use of the genetic algorithm will be briefly discussed in this chapter. In addition, the limitation of the use of brute-force optimisation will be pointed out. The chapter will also discuss the effect of the selection of the cut-off power level as well as the antenna polarisation on the optimisation process.

In order to demonstrate that the observations discussed in this chapter are not environment specific, another indoor environment is considered in different circumstances too and the optimal base stations' locations as well as the minimal amount of emitted power are presented in Appendix A. it is shown that the optimal base stations' positions and minimal amount of emitted power are affected by the cost function's parameters as well as the environment dynamic based on the same trends discussed in this chapter.

5.2 Cost Function Definition

The cost function defined in this section is calculated based on the path loss values at all the possible receivers' positions. It is defined based on two statistical measures, the path loss average and standard deviation. The objective function is therefore formed of two parts. The first part calculates the average of the path loss

values while the second calculates the corresponding standard deviation. Minimising the average path loss provides an overall good coverage throughout the environment. On the other hand, knowing that the standard deviation represents how far the data it represents is from the average, the minimisation of this statistical measure reduces the maximum attained path loss values, which improves the path loss at the worst positions, then depending on the receiver's sensitivity a certain position may or may not enjoy the service. The equation of the cost function is then:

$$f = \alpha \overline{PL} + (1 - \alpha) \sigma_{PL} \quad (5.1)$$

where \overline{PL} is the average path loss, σ_{PL} is the path loss standard deviation. The factor α is a trade-off factor selected within the range $[0, 1]$. It is used to specify whether the average or the standard deviation should have higher influence on the cost function.

Instead of treating the various areas of the environment equally, each area may be prioritised through weighting factors selected depending on how frequently the area is likely to be occupied by users. The objective function becomes then:

$$f = \alpha \frac{1}{N} \sum_{i=1}^N w_i PL_i + (1 - \alpha) \sqrt{\frac{1}{N} \sum_{i=1}^N \left(w_i PL_i - \frac{1}{N} \sum_{j=1}^N w_j PL_j \right)^2} \quad (5.2)$$

w_i is the priority weight at the i^{th} possible receiver's position, PL_i is the path loss of the i^{th} receiver position and N is the number of possible receivers' positions. When multiple transmitters are assumed to serve the environment, each receiver's position is allocated to the base station providing the highest field strength (minimal path loss). Note that a brute force optimisation approach is used to find the optimal base stations' coordinates where the cost function is defined over a discrete set of base stations' coordinates shown in chapter 4 (Figure 4.3). However, genetic algorithm will be tested in section 5.7 and the results will be compared with that of brute-force optimisation.

5.3 Power Minimisation Algorithm

After finding the optimal base stations' locations, the next step is to calculate the minimal amount of emitted power required to provide a certain coverage percentage over the environment. A receiver enjoys the wireless service if it receives a signal

strength that is at least equal to the receiver's sensitivity. The receiver's sensitivity is device dependent. In this chapter, it will be set to -65 dBm [60]. Recalling that the path loss in dB is the difference between the transmitted and received power, a critical or threshold path loss value can be found based on the receiver's sensitivity as follows:

$$PL_{th}(dB) = P_t - (P_r)_{min} \quad (5.3)$$

where PL_{th} is the path loss threshold, P_t is the transmitted power and $(P_r)_{min}$ is the minimal power a receiver must acquire to enjoy the service and it is equal to the receiver's sensitivity. Consequently, any receiver's position with a path loss above the path loss threshold does not have coverage.

The minimal emitted power is found iteratively. Starting with a high transmitted power, the path loss threshold is calculated based on equation 5.3 and the percentage of receivers' locations with path loss less than the threshold is calculated and compared to a predefined required coverage percentage. As long as the calculated coverage percentage is higher than the required coverage, the transmitted power is decreased and the process repeats. When the calculated coverage percentage reaches the required coverage, the transmitted power is considered the minimal required power. Note that the power decrement depends on how far the calculated coverage is from the desired coverage. It starts with a value of 1 dBm and as the calculated coverage approaches the desired coverage, the decrement is refined to 0.01 dBm. Figure 5.1 shows the flow chart of the power minimisation algorithm. Note that when multiple base stations are serving the environment, it is assumed that they all provide the same amount of emitted power. Furthermore, based on [61] and [62], the maximum power used in the 802.11 family is 1000 mW (30 dBm) although this varies with countries. Consequently, when the minimal emitted power calculated later in this chapter, for a given coverage percentage, is higher than 30 dBm per base station, the value is beyond the allowable power level and the desired coverage cannot be achieved in real systems.

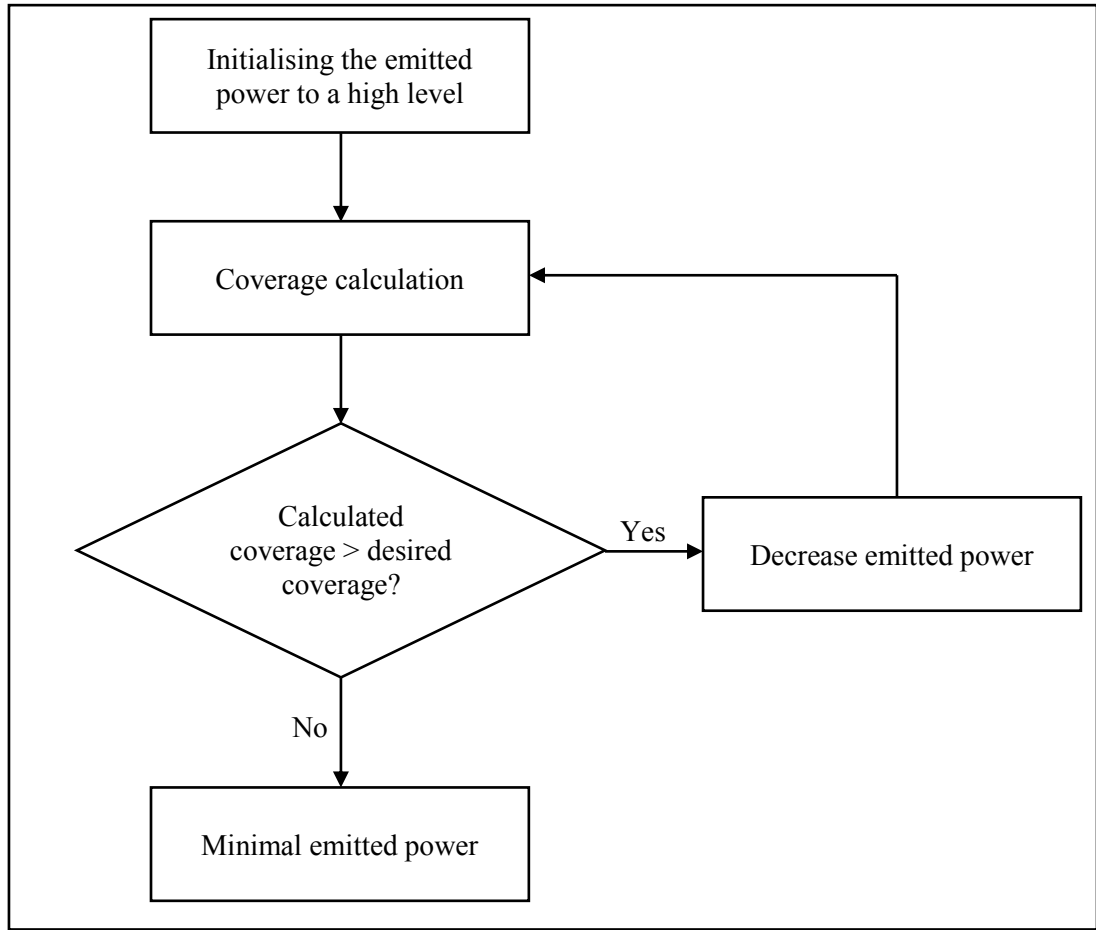


Figure 5.1: Power minimisation algorithm flow chart

5.4 Optimal Base Stations' Locations and Minimal Power in The Empty Environment

The first environment's configuration to be considered in this chapter is the empty environment with all windows and doors closed. In an empty environment, it is hard to specify places where a receiver is more likely to be, thus no priority weights can be estimated and the cost function will be used without priority weights as defined in equation 5.1.

The parameter that can be varied in this case is the trade-off factor (α). Note that the trade-off factor was varied over its complete range and a selection will be shown in this chapter, mainly the ones that shows a change in the optimal base station's locations. When the trade-off factor is lower than 0.5, higher importance is given to the standard deviation and the number of receivers' location with high path loss will be reduced. For a trade-off of 0.2, the optimal base station's coordinates are (7.175, 11.725). When the

trade-off factor is increased to 0.7, higher impact is given to the average and the optimal base station's coordinates become (5.675, 8.725). Figure 5.2 shows the path loss throughout the environment when the base station is located at its optimal position obtained for the trade-off factors of 0.2 and 0.7. Note that the locations where a receiver cannot exist appear in dark blue. It can be seen that when higher importance is given to the standard deviation ($\alpha=0.2$), the base station is located in the centre of the environment trying to provide both ends of the environment higher field strength (lower path loss) compared to the case of higher trade-off where the base station is shifted in a way to increase the area around it with low path loss values to keep an overall good coverage even if this is at the cost of higher number of receivers' locations with high path loss. As an example, for the optimal position obtained based on $\alpha=0.2$, 4.22% of the possible receivers' positions have their path loss greater than 100 dB as opposed to 5.67% when $\alpha=0.7$. Note that a possible receiver's position means any free space location inside the environment with the exclusion of some places like the inner parts of the cabinets or the fridge even if they are modelled as free space cells. Concerning the minimal emitted power and based on a receiver's sensitivity of -65 dBm, 18.53 dBm and 18.05 dBm are required to provide 80% coverage throughout the environment for the optimal positions with coordinates (7.175, 11.725) and (5.675, 8.725) respectively.

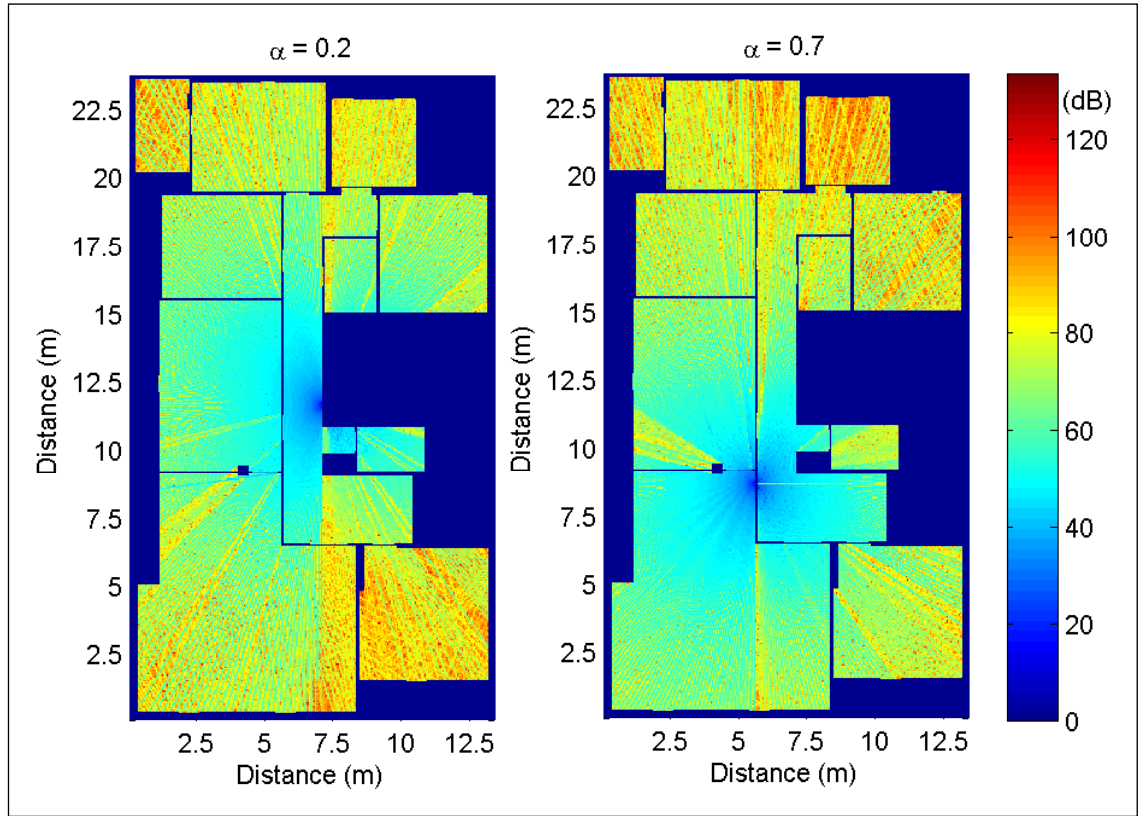


Figure 5.2: Path loss in dB at the possible receivers' positions throughout the empty environment when the transmitter is at its optimal location for trade-off factor equals 0.2 and 0.7

Furthermore, the use of multiple base stations decreases the total amount of power needed to cover the environment [57] which in turn reduces the power consumption as well as the interference with other base stations in neighbour environments, thus two and then three transmitters are assumed to serve the environment.

The minimisation of equation 5.1 when two base stations are serving the empty environment lead to the coordinates of (7.175, 5.725) and (5.675, 19.225) for trade-off factor $\alpha=0.2$ and of (5.675, 5.725) and (5.675, 19.225) for $\alpha=0.7$. The path loss distribution over the environment is shown in Figure 5.3. It is clear that the use of a second base station has improved the overall service by decreasing the maximal attained path loss value. Comparing the optimal positions obtained for the different trade-off factor values, the base station serving the southern half of the environment is shifted eastward when higher priority is given to the standard deviation part of the cost function ($\alpha=0.2$) so that lower path loss is obtained mainly in the south east side of the environment as well as part of the corridor. As for the emitted power necessary to

provide 80% coverage, it is -0.36 dBm and -0.28 dBm per base station, that is the total emitted power using two base stations is 38.72 and 34.03 times less than that when a single transmitter is serving the environment for $\alpha=0.2$ and $\alpha=0.7$ scenarios respectively. Note that when the cost function is defined to be equal to the standard deviation only ($\alpha=0$), the optimal positions are the same obtained for $\alpha=0.2$ for the single and two transmitters cases. Similarly, when the cost function is defined as the average path loss only ($\alpha=1$), the optimal positions are the same obtained for $\alpha=0.7$ for the single and two transmitters cases.

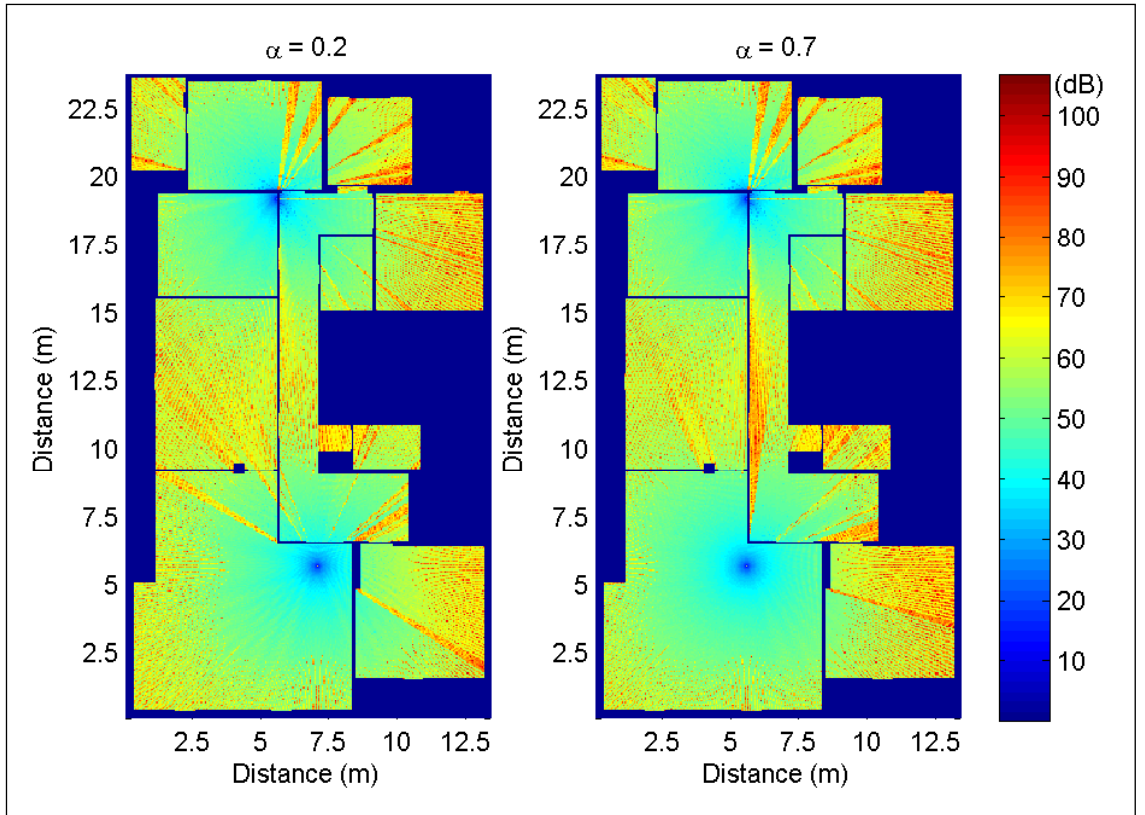


Figure 5.3: Path loss in dB at the possible receivers' positions throughout the empty environment when two transmitters are at their optimal locations for trade-off factor equals 0.2 and 0.7

Assuming that three base stations are serving the environment, the optimal base stations' coordinates when higher priority is given to the average path loss in the definition of the cost function ($\alpha=0.7$ or 1) are (7.175, 4.225), (4.175, 11.725) and (5.675, 19.225). Each base station is somehow centred within the area it is serving and must emit -6.55 dBm so that the three base stations cover 80% of the environment

assuming that the receiver's sensitivity is -65 dBm. Consequently, the use of three transmitters, in this case, reduces the total amount of power by 96.13 times and 2.82 times compared to the single and two transmitters' scenarios respectively. On the other hand, while decreasing the trade-off factor to give higher impact to the standard deviation, the base station located at (4.175, 11.725) is shifted eastward to the location (7.175, 11.725) when $\alpha=0.2$ and then northward to (7.175, 13.225) when $\alpha=0$ while the other two base stations' optimal locations did not vary compared to the case when $\alpha=0.7$ or 1. The main reason behind this movement is to reduce the high path loss values in the regions circled in red in Figure 5.4 that shows the path loss distribution throughout the environment for the trade-off factor values of 0, 0.2 and 0.7.

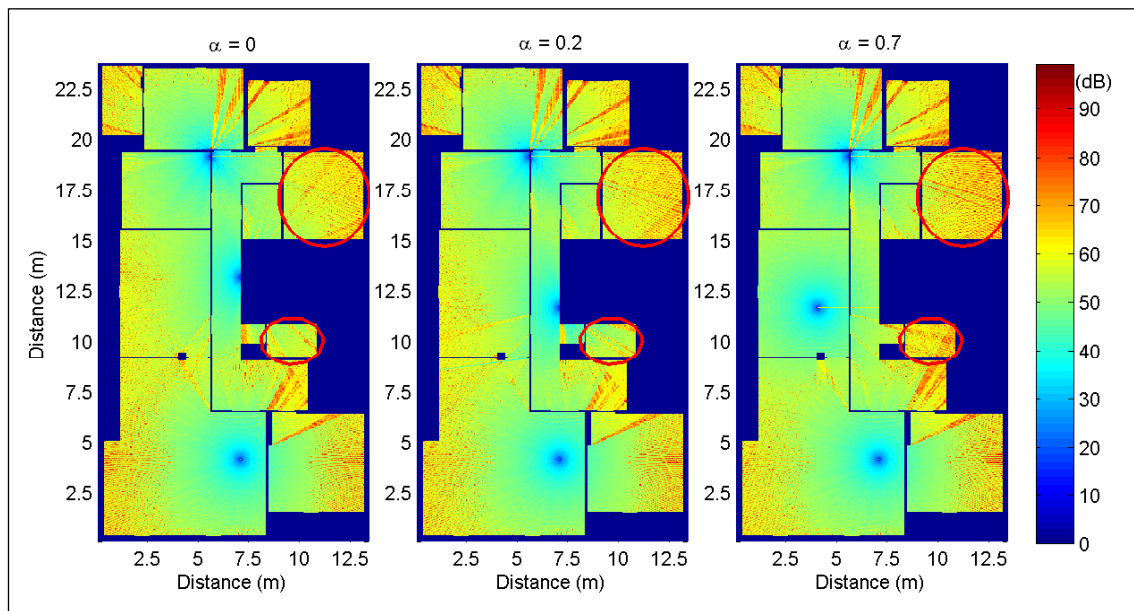


Figure 5.4: Path loss in dB at the possible receivers' positions throughout the empty environment when three transmitters are at their optimal locations for trade-off factor equals 0, 0.2 and 0.7

5.5 Effect of Environment Changes on The Optimal Base Stations' Location and The Minimal Power

An indoor environment cannot be empty, it will be furnished and this will have an effect on the path loss distribution which in turn may affect the optimal base stations' positions as well as the minimal amount of emitted power to provide a predefined coverage. In addition, people will be present in the environment and changes such as

windows or doors opening may occur in the environment which also affect the performance of the wireless system. In order to check the effect of adding furniture to the environment and that of environment changes, the same environment previously considered empty in section 5.4 will be considered in three different circumstances. In the first case the environment is considered furnished with all windows and doors closed, it will be designated as the closed environment throughout the chapter. The second scenario is a modification of the closed environment where all windows and almost all doors (excluding the main door) will be considered open and it will be denoted as the open environment. As for the last case, people will be added to the closed environment denoted as the environment with people (people locations are shown in chapter 4).

The cost function previously defined in this chapter will be minimised for the three scenarios when the environment is assumed to be served by one, two or three base stations. Unlike the empty environment case, in a furnished environment the locations where a receiver is more likely to use the service can be estimated, thus the cost function will be minimised in its two forms (equations 5.1 and 5.2). Each possible receiver's position will be assigned a priority weight equal to 1, 2 or 3. Two distributions are used with one having high priority weights positions condensed in the southern half of the environment as indicated in Figure 5.5 where the cyan colour represents receivers' positions with priority weights equal 1, the yellow and red these with priority weights of 2 and 3 respectively. As for the dark blue, it represents positions where a receiver cannot exist.

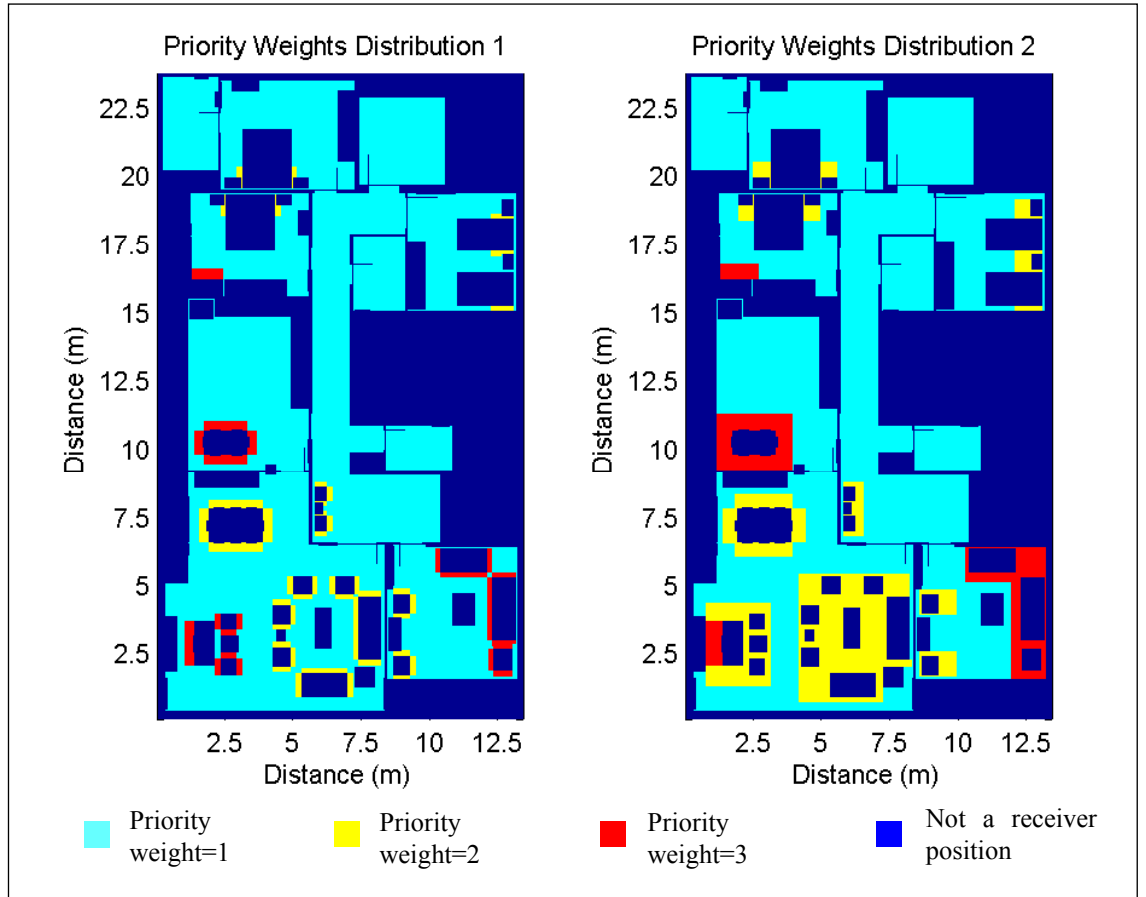


Figure 5.5: Priority weight values throughout the furnished environment (2 distributions)

5.5.1 Single Transmitter Scenario

First of all, one base station is assumed to serve the environment. The minimisation of the cost function without priority weights (equation 5.1) in the closed environment lead to the location with coordinates (7.175, 13.225) for trade-off values of 0, 0.2 and 0.7 with 30.66 dBm to cover 80% of the environment when the receiver's sensitivity is -65 dBm. When the cost function becomes equal to the average path loss by setting the trade-off to 0, the optimal location is shifted southward to settle in the middle of the environment at (7.175, 11.725) with 30.92 dBm for the minimal power. As for the open environment and the environment with people, the central base station's location at (7.175, 11.725) is the only position that minimises the cost function regardless of the trade-off factor values. The amount of power required to provide 80% coverage is 31.5 dBm in the open environment and 31.89 dBm in the environment with people which are slightly higher than that needed when the base station is at the same position in the closed environment. Table 5.1 summarises the coordinates of the optimal

base station's positions in addition to the minimal amount of power that provides service to 80% of the possible receivers' positions based on -65 dBm sensitivity for the four environment's configurations when no priority weights are used as well as when the priority weights are selected based on the two distributions (D1 and D2) shown in Figure 5.5 for trade-off values of 0, 0.2, 0.7 and 1. Recall from section 5.3 that any power level greater than 30 dBm is not applicable in real indoor environments therefore the 80% coverage cannot be achieved.

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(7.175, 11.725) 18.53 dBm	(7.175, 11.725) 18.53 dBm	(5.675, 8.725) 18.05 dBm	(5.675, 8.725) 18.05 dBm
	$W_i=1$	(7.175, 13.225) 30.66 dBm	(7.175, 13.225) 30.66 dBm	(7.175, 13.225) 30.66 dBm	(7.175, 11.725) 30.92 dBm
Closed Environment	$W_i=1, 2$ or 3 (D1)	(5.675, 7.225) 36.58 dBm	(10.175, 8.725) 33.36 dBm	(7.175, 11.725) 30.92 dBm	(7.175, 11.725) 30.92 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 7.225) 36.58 dBm	(5.675, 7.225) 36.58 dBm	(7.175, 8.725) 32.49 dBm	(7.175, 8.725) 32.49 dBm
	$W_i=1$	(7.175, 11.725) 31.5 dBm	(7.175, 11.725) 31.5 dBm	(7.175, 11.725) 31.5 dBm	(7.175, 11.725) 31.5 dBm
Open Environment	$W_i=1, 2$ or 3 (D1)	(5.675, 7.225) 36.74dBm	(5.675, 7.225) 36.74dBm	(7.175, 11.725) 31.5 dBm	(7.175, 11.725) 31.5 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 5.725) 40.19 dBm	(5.675, 7.225) 36.74dBm	(7.175, 8.725) 34.32 dBm	(7.175, 11.725) 31.5 dBm
	$W_i=1$	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm
Environment with People	$W_i=1, 2$ or 3 (D1)	(5.675, 7.225) 39.94 dBm	(5.675, 7.225) 39.94 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 7.225) 39.94 dBm	(5.675, 7.225) 39.94 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm
	$W_i=1$	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm	(7.175, 11.725) 31.89 dBm

Table 5.1: Optimal base station's coordinates and minimal amount of emitted power required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty, closed and open environments as well as the environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1

In order to explore the effect of the furniture addition on the path loss values, the base station is located at (7.175, 11.725) and the path loss throughout the empty and closed environment are plotted (Figure 5.6). Based on the 2D channel model adopted, it is clear that the addition of furniture to the environment weakens the signal through reflections accompanied with absorption that the signal undergoes which terminates the signal earlier compared to the case where the environment is empty. Consequently higher path loss values are attained in the furnished environment. This can be further seen while comparing the minimal amount of emitted power required in both environments to reach the same coverage percentage. The empty environment requires 18.53 dBm to attain 80% coverage while the closed environment requires 30.92 dBm. This means that the closed environment requires 17.33 times more power as opposed to the empty environment to provide service for 80% of the possible receivers' positions.

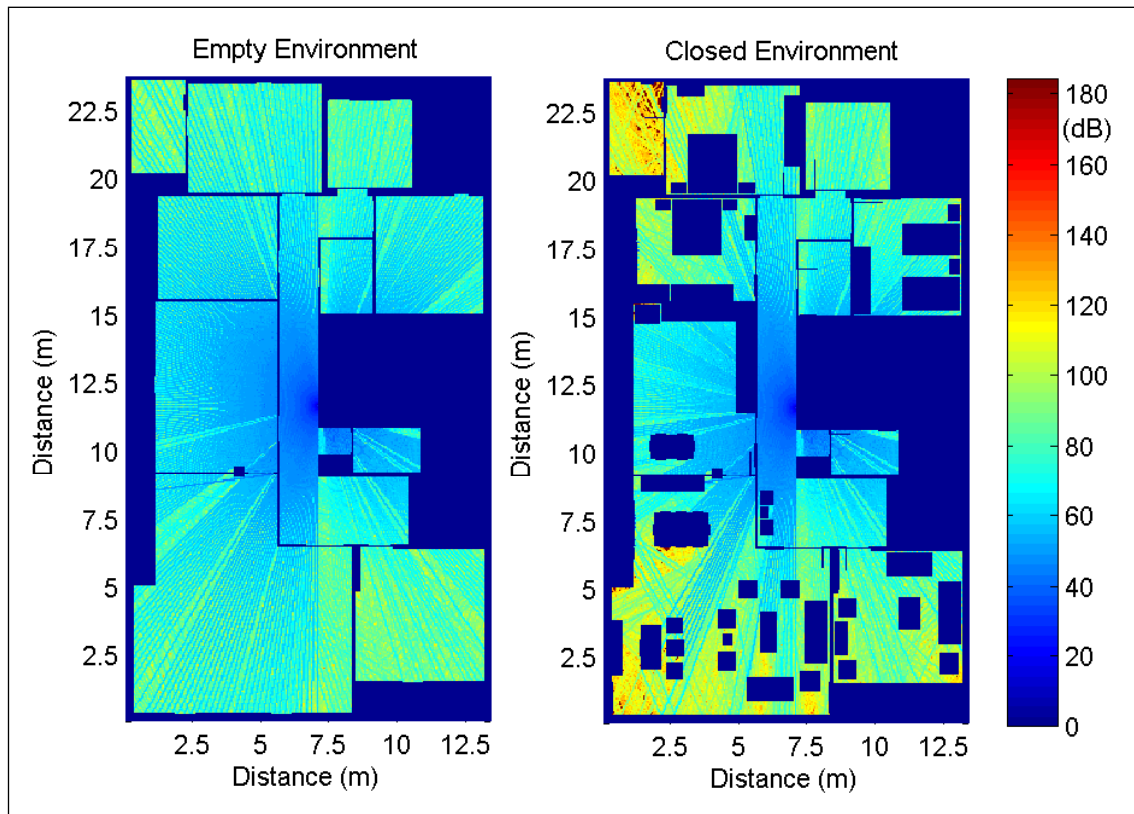


Figure 5.6: Path loss in dB at the possible receivers' positions throughout the empty and closed environments for the base station position with coordinates (7.175, 11.725)

Attempting to understand why the same optimal position is obtained for different trade-off factor values for the open environment, the path loss through the environment is plotted in Figure 5.7 when the base station is located at the optimal position (7.175, 11.725) and at the one obtained in the closed environment when higher priority is given to the standard deviation which is (7.175, 13.225). In the case of the closed environment, the optimal transmitter's position is displaced northward from (7.175, 11.725) to (7.175, 13.225) in order to improve the path loss in the north west corner of the environment. However, in the open environment, when the base station is at (7.175, 13.225) the path loss at the north west side of the environment is improved as can be seen in Figure 5.7 but the path loss at the southern part of the environment has deteriorated in a way that the central position at (7.175, 11.725) is the one that not only minimises the average path loss but also decreases the number of receivers' positions with high path loss.

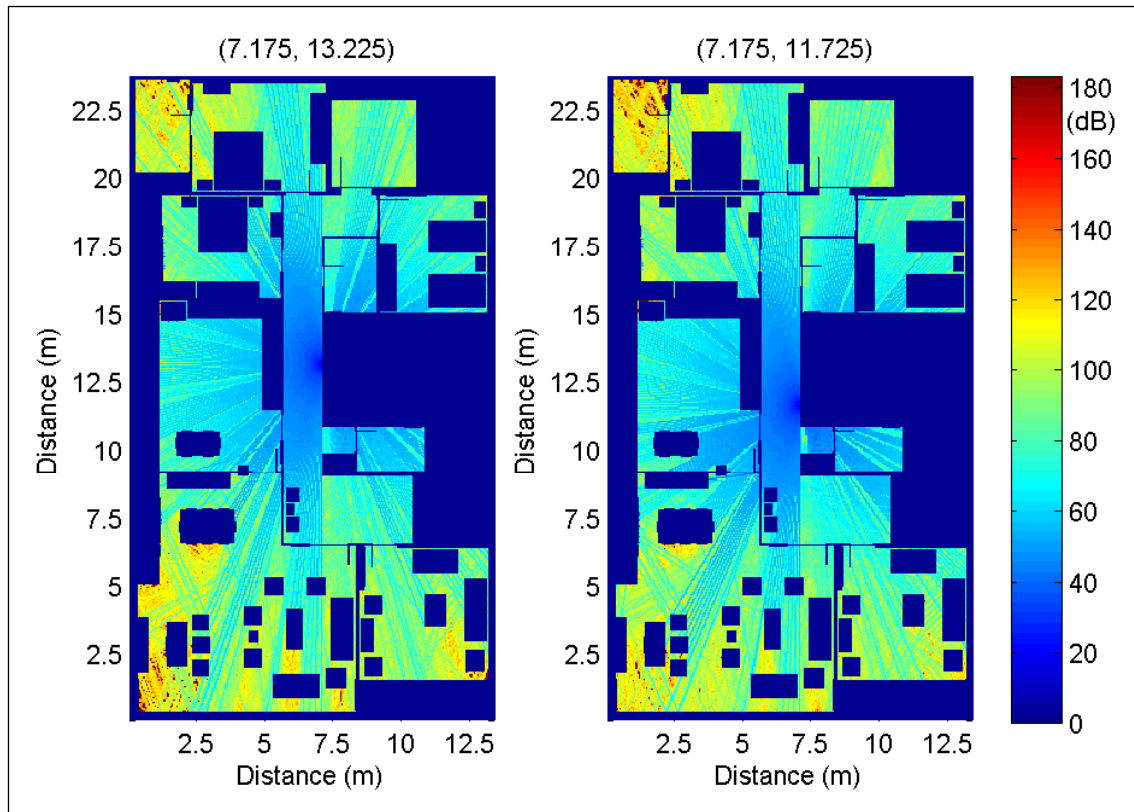


Figure 5.7: Path loss in dB at the possible receivers' positions throughout the open environment for the base station positions with coordinates (7.175, 13.225) and (7.175, 11.725)

Similarly the same base station's position at (7.175, 11.725) is obtained in the environment with people when the trade-off factor is varied. The path loss through the environment at the optimal location (7.175, 11.725) and the optimal location of the closed environment when a low trade-off is used ((7.175, 13.225)) are presented in Figure 5.8. When the transmitter is located at (7.175, 13.225), a person circled in black in Figure 5.8 blocks the signal and reduces its strength which led to two regions with the highest path loss circled in red on the west side of the environment. In addition a third region of high path loss exists on the south east side of the environment. These three regions with high path loss are clearly bigger than the ones obtained when the base station is at (7.175, 11.725) which make it the optimal location regardless of the trade-off value selection. Note that the presence of the same person obstructs the signal generated from the base station at its optimal location though the effect is smaller as the distance the obstructed rays need to travel is much smaller and the path loss values do not reach very high values.

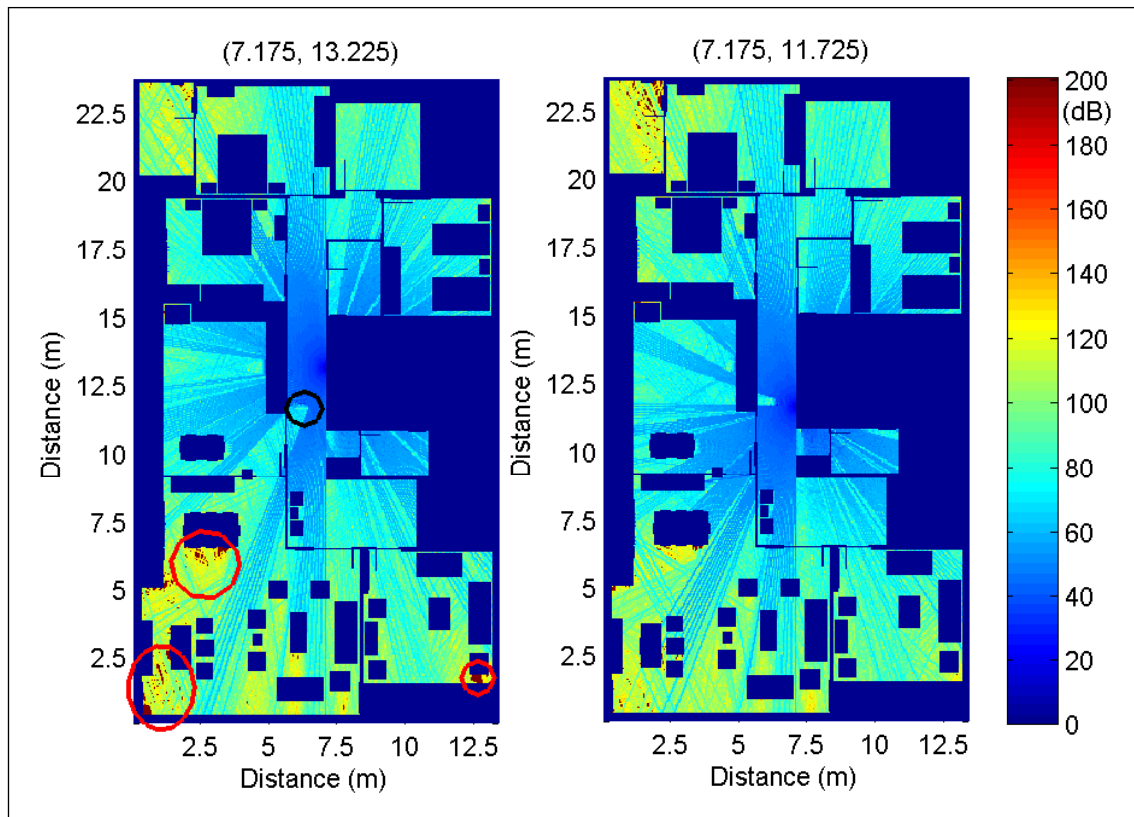


Figure 5.8: Path loss in dB at the possible receivers' positions throughout the environment with people for the base station positions with coordinates (7.175, 13.225) and (7.175, 11.725)

On the other hand, the introduction of priority weights to the cost function calculations shifts the optimal base station's location closer to the area with the highest number of possible receivers' positions having high priority weights. In the closed environment and when the priority weights are assigned based on distribution 1 previously shown in Figure 5.5, the optimal base station's position is at (5.675, 7.225) when the cost function is formulated as the standard deviation alone ($\alpha=0$). In this way, the most possible receivers' positions with high priority possess low path loss values. As the trade-off factor is increased, the optimal base station is displaced farther from the area crowded with possible receivers' positions having high priority to reach (10.175, 8.725) when $\alpha=0.2$ and then (7.175, 11.725) when $\alpha=0.7$ or 1. Figure 5.9 shows the path loss through the closed environment when the base station is placed at its optimal position for the various trade-off factor values.

Similarly, the optimal base station's location started close to the area having the most possible receivers' locations with high priority assigned based on distribution 2 when the trade-off factor is equal to 0. In fact, the optimal position is the same obtained when the priority weights are assigned based on distribution 1 for the trade-off factor of 0. However, when the trade-off factor is increased, the optimal base station's position does not move like in the case when the priority weights of distribution 1 are used. This is because the priority weights of distribution 2 are more condensed and they are highly affecting the standard deviation value. The base station is then relocated at (7.175, 8.725) when the trade-off factor is changed to 0.7 or 1 though not as far as the one obtained for the lower density priority weights. Figure 5.10 shows the path loss distribution over the possible receivers' locations in the closed environment for the resulting optimal base station's locations based on the second priority weights distribution. Thus, when higher priority is given to the standard deviation, the optimal base station's position prevents receivers' locations with high priority from having the highest path loss values available throughout the environment. As the trade-off factor is increased, the base station relocates farther from the high priority receivers' positions and more receivers' positions are allowed to have high path loss while the weighted average path loss is minimal. Note that when the priority weights distribution is not assigned in large clusters, the optimal base station's position when the trade-off factor is 0 can be equal to that obtained when the receivers' positions are not assigned priority weights. On the other hand, the more the priority weights distribution is assigned in

larger clusters, the optimal location stays close to the area with the highest number of receivers' positions having high priority even when the trade-off factor is increased but not as close as when low trade-off factor values are used.

Concerning the minimal amount of power required to provide service to 80% of the possible receivers' positions, the more the optimal base station's position is shifted southward in the environment to get closer to the possible receivers' locations with high priority, the more the minimal power is increased. The highest required power, when the base station is at its lowest position at (5.675, 7.225), is 36.58 dBm. As the base station moved higher toward the centre of the environment the minimal amount of required power gets lower. The power values for the various obtained optimal base station's locations are shown in Table 5.1.

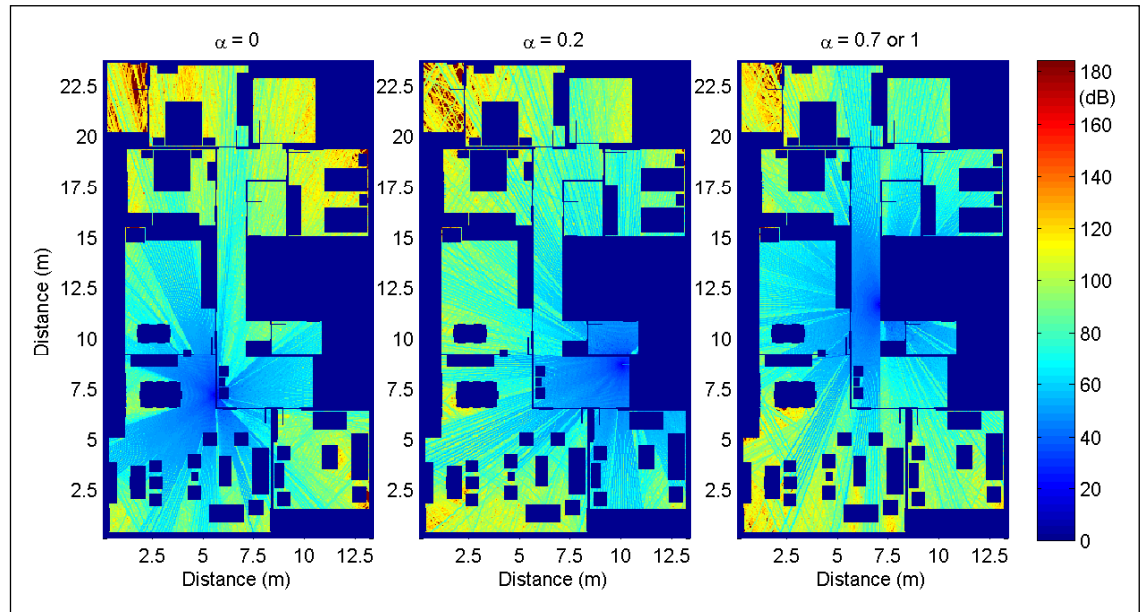


Figure 5.9: Path loss in dB at the possible receivers' positions throughout the closed environment for the trade-off factor values of 0, 0.2, 0.7 and 1 with priority weights based on distribution 1

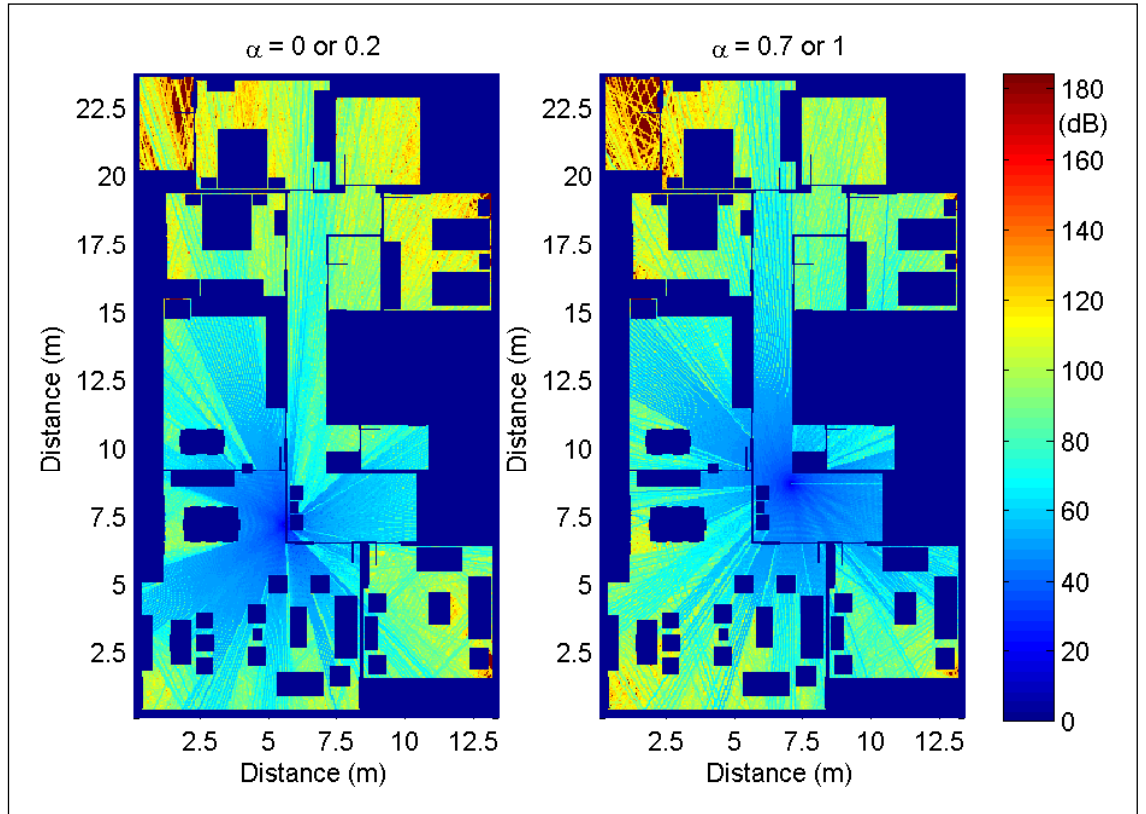


Figure 5.10: Path loss in dB at the possible receivers' positions throughout the closed environment for the trade-off factor values of 0, 0.2, 0.7 and 1 with priority weights based on distribution 2

Furthermore, the base station relocates in the open environment as well as in the environment with people when the priority weights are added to the cost function calculations based on the same trend previously described for the closed environment though sometimes different optimal locations are obtained compared to these obtained in the closed environment. The optimal coordinates are shown in Table 5.1. For example, when the priority weights based on distribution 2 are used, the optimal position's coordinates obtained in the environment with people are equal to those obtained in the closed environment for the trade-off values of 0 and 0.2 whereas different coordinates are achieved when higher priority is given to the average ($\alpha=0.7$ or 1). The optimal position of the closed environment is at (7.175, 8.725), once people settle in the environment two of the persons are highly affecting the rays emitted by the base station located at (7.175, 8.725) making it no longer suitable as the optimal location and the location (7.175, 11.725) fulfils the minimisation of the cost function instead. In this case, when high trade-off factor values are used, even the high density priority weights distribution is not able to keep the optimal position close to the area

with the highest number of receivers' positions having high priority weights and a central position is obtained.

In addition, the amount of power required to cover 80% of the possible receivers' positions increases when the optimal position moves away from the centre of the environment as, to cover the required percentage, positions far from the base station must get enough signal strength and thus higher emitted power is required. Note that for the same base station's position, the closed environment requires the least amount of power then comes the open environment and finally the environment with people. When the base station is placed at (5.675, 7.225) for example, the environment with people requires double the amount of power needed in the closed environment which shows that the presence of people blocks the signal and allows a lesser portion of the signal to travel further in the environment through absorption.

5.5.2 Two Transmitters Scenario

Examining the minimal amount of power required to cover 80% of the possible receivers' positions in the furnished environment, it is clear that there is a need to decrease it while maintaining the same target coverage, thus another base station should assist the first one accomplishing this mission.

First of all, considering the closed environment, the minimisation of the cost function of equation 5.1 (i.e. without the use of priority weights), led to the optimal positions with coordinates (5.675, 5.725) and (7.175, 19.225) when the trade-off factor is set to 0.7 or 1 whereas when the trade-off factor is reduced to 0.2 or 0, higher priority is given to the standard deviation and the optimal position coordinates of the two base stations change to (5.675, 5.725) and (5.675, 19.225). Figure 5.11 shows the path loss distribution for these two optimal locations. It is visible that when the trade-off factor is decreased to 0 or 0.2, the base station located in the northern part of the environment moves eastward so that the path loss values in the north west corner of the environment decrease although the signal level at other areas drops to some extent. Compared to the empty environment optimal positions, different but close optimal positions' coordinates are obtained. In addition, in the empty environment, the area having the highest path loss values was in the south east part of the environment, thus when the trade-off factor was decreased, the base station in the southern part of the environment was the one to relocate by moving eastward (Figure 5.3).

Furthermore, the use of the second base station has decreased the path loss values through the environment and the total amount of power required to provide 80% coverage has decreased accordingly. When the trade-off factor is set to 0.2, the minimal amount of power when the closed environment is served by a single transmitter is 30.66 dBm while it is 15.33 dBm per base station after adding the second one. The total amount of required power is then 17 times lower.

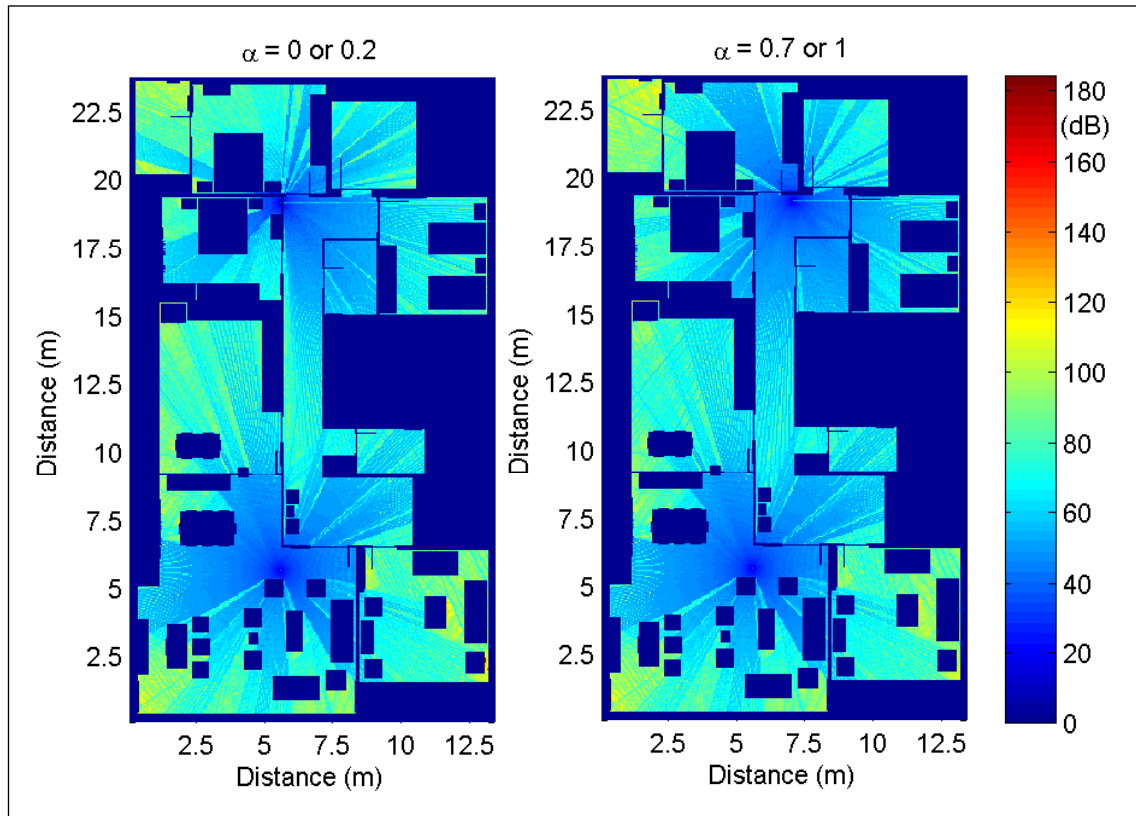


Figure 5.11: Path loss in dB at the possible receivers' positions throughout the closed environment when two transmitters are at their optimal locations for trade-off factor equals 0, 0.2, 0.7 and 1

On the other hand, the same optimal positions obtained for the closed environment, when no priority weights are assigned to the possible receivers' positions, are obtained for the open environment as well as the environment with people though with higher minimal amount of emitted power. The changes that opening the doors and windows introduced to the path loss values are not high enough to change the optimal base stations' locations. Furthermore, there are no people close to the base stations to highly obstruct the signal, thus the path loss distribution is not greatly affected in a way

that allows other base stations' locations to optimise the cost function. Table 5.2 shows the different optimal base stations' coordinates along with the minimal amount of power required to cover 80% of the various environment's configurations when the receiver's sensitivity is assumed to be -65 dBm for different trade-off values and priority weights.

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(7.175, 5.725) (5.675, 19.225) -0.36 dBm	(7.175, 5.725) (5.675, 19.225) -0.36 dBm	(5.675, 5.725) (5.675, 19.225) -0.28 dBm	(5.675, 5.725) (5.675, 19.225) -0.28 dBm
Closed Environment	$W_i=1$	(5.675, 5.725) (5.675, 19.225) 15.33 dBm	(5.675, 5.725) (5.675, 19.225) 15.33 dBm	(5.675, 5.725) (7.175, 19.225) 14.03 dBm	(5.675, 5.725) (7.175, 19.225) 14.03 dBm
	$W_i=1, 2$ or 3 (D1)	(8.675, 4.225) (1.275, 13.225) 27.74 dBm	(5.675, 5.725) (5.675, 16.225) 16.11 dBm	(5.675, 5.725) (5.675, 16.225) 16.11 dBm	(5.675, 5.725) (7.175, 19.225) 14.03 dBm
	$W_i=1, 2$ or 3 (D2)	(13.175, 5.725) (5.675, 7.225) 29.72 dBm	(13.175, 5.725) (5.675, 7.225) 29.72 dBm	(5.675, 5.725) (5.675, 16.225) 16.11 dBm	(5.675, 5.725) (7.175, 19.225) 14.03 dBm
Open Environment	$W_i=1$	(5.675, 5.725) (5.675, 19.225) 15.47 dBm	(5.675, 5.725) (5.675, 19.225) 15.47 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm
	$W_i=1, 2$ or 3 (D1)	(13.175, 5.725) (5.675, 7.225) 30.05 dBm	(5.675, 5.725) (5.675, 16.225) 18.06 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm
	$W_i=1, 2$ or 3 (D2)	(13.175, 5.725) (5.675, 7.225) 30.05 dBm	(13.175, 5.725) (5.675, 7.225) 30.05 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm	(5.675, 5.725) (7.175, 19.225) 14.98 dBm
Environment with People	$W_i=1$	(5.675, 5.725) (5.675, 19.225) 16.46 dBm	(5.675, 5.725) (5.675, 19.225) 16.46 dBm	(5.675, 5.725) (7.175, 19.225) 15.37 dBm	(5.675, 5.725) (7.175, 19.225) 15.37 dBm
	$W_i=1, 2$ or 3 (D1)	(8.675, 4.225) (1.275, 13.225) 28.2 dBm	(5.675, 5.725) (5.675, 16.225) 17.34 dBm	(5.675, 5.725) (5.675, 16.225) 17.34 dBm	(5.675, 5.725) (7.175, 19.225) 15.37 dBm
	$W_i=1, 2$ or 3 (D2)	(8.675, 4.225) (1.275, 13.225) 28.2 dBm	(8.675, 4.225) (1.275, 13.225) 28.2 dBm	(5.675, 5.725) (5.675, 16.225) 17.34 dBm	(5.675, 5.725) (7.175, 19.225) 15.37 dBm

Table 5.2: Optimal base stations' coordinates and minimal amount of emitted power per base station required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty, closed and open environments as well as the environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1 (2 base stations)

Assigning priority weights to each possible receiver's position and repeating the minimisation process for the three furnished environment's configurations leads to different positions compared to those obtained in the absence of priority weights. The only exceptions are when the trade-off factor is set to 1 in the various environment forms as well as when the trade-off factor is set to 0.7 in the open environment where each of the base stations is located somehow in the centre of the area it is serving ((5.675, 5.725) and (7.175, 19.225)) providing the best overall coverage.

In contrast, when higher importance is given to the standard deviation value in the cost function definition, the optimal base stations' locations get closer to the zones having more high priority receivers' positions. Based on both priority weights distributions, the southern half of the environment contains more receivers' positions with high priority weights and this is where the two base stations are located for the low trade-off factor values. Furthermore, when the more condensed priority weights distribution is used (referred as D2), the two base stations' locations are close to each other.

As an example, when the closed environment is considered, the optimal base stations' coordinates when the priority weights are selected based on distributions 1 and 2 with trade-off factor of 0 are (8.675, 4.225) and (1.275, 13.225) as well as (13.175, 5.725) and (5.675, 7.225) respectively. Figure 5.12 that shows the path loss in the closed environment when the base stations are at their optimal locations for different priority weights values illustrates how much closer the two base stations get when the more condensed priority weights distribution is used. However, while the southern part of the environment is having low path loss values, the northern part suffers from high path loss values. Thus to keep the 80% coverage, additional power is needed so that enough field strength reaches the northern part of the environment. The minimal power is 27.47 times more when the priority weights of distribution 2 are used as opposed to the case with no priority weights assigned to receivers' locations. As for the receivers' allocation into the two base stations, when the base stations are too close to each other ((13.175, 5.725) and (5.675, 7.225)), the receivers are not fairly distributed among the base stations. The base station BS1 at (13.175, 5.725) serves 33.51% of the possible receivers' locations while the base station BS2 at (5.675, 7.225) serves 66.49%. As soon as the base stations move apart to (8.675, 4.225) and (1.275, 13.225), the receivers' allocation is more balanced between the two base stations where the first one is

responsible of 47.78% of the receivers and the second is responsible of 52.22%. Figure 5.13 shows the receivers' allocation among the two base stations for the base stations' locations of (8.675, 4.225) and (1.275, 13.225) as well as (13.175, 5.725) and (5.675, 7.225).

When the trade-off factor is increased to 0.2, the two base stations start to move apart from each other with one of them approaching the northern half of the environment when the priority weights of distribution 1 are used. However, when the high density priority weights (referred as D2) are used, the base stations do not relocate and remain at the optimal locations achieved when the trade-off is 0 and this applies to the three furnished environment's configurations.

Increasing the trade-off factor further to 0.7, the two base stations stay at the optimal positions obtained for $\alpha=0.2$ when they already moved away in the latter case or they go even farther from each other. The optimal positions based on both priority weights distributions become equal and this again is the case of the three environment setups.

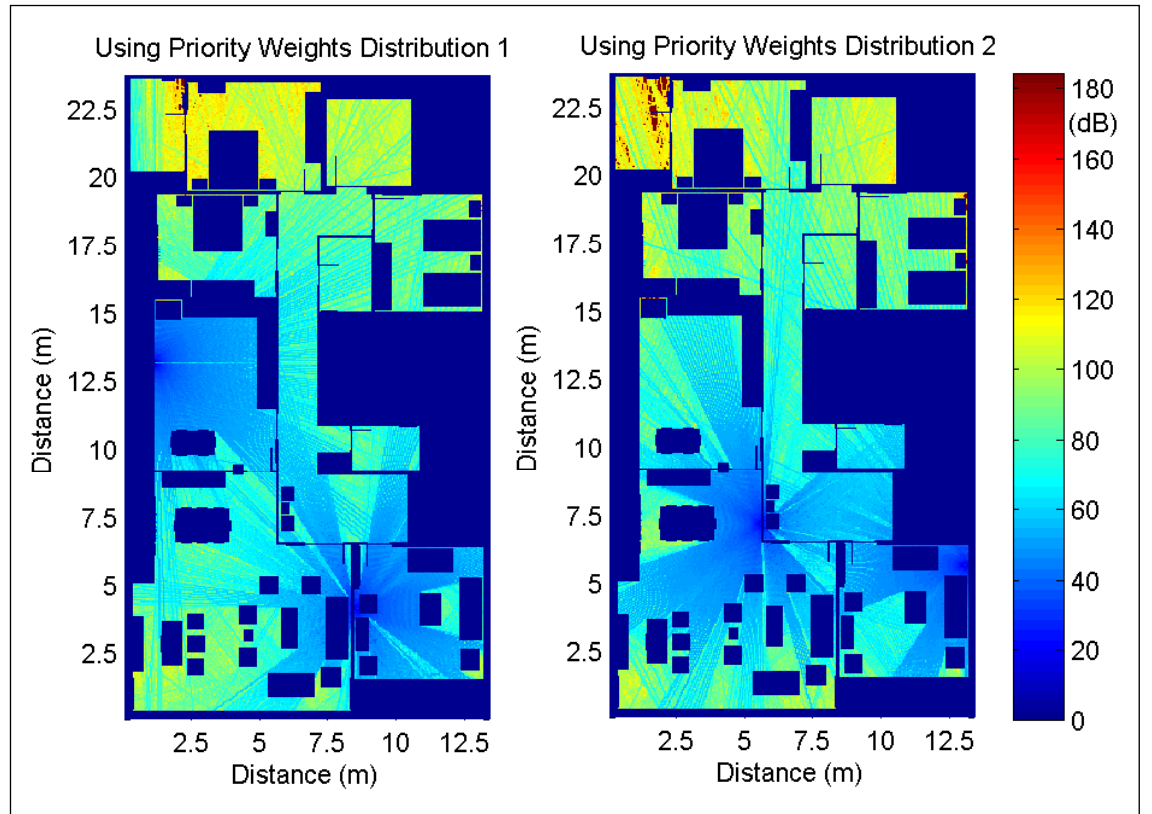


Figure 5.12: Path loss in dB at the possible receivers' positions throughout the closed environment when two transmitters are at their optimal locations for different priority weights distributions

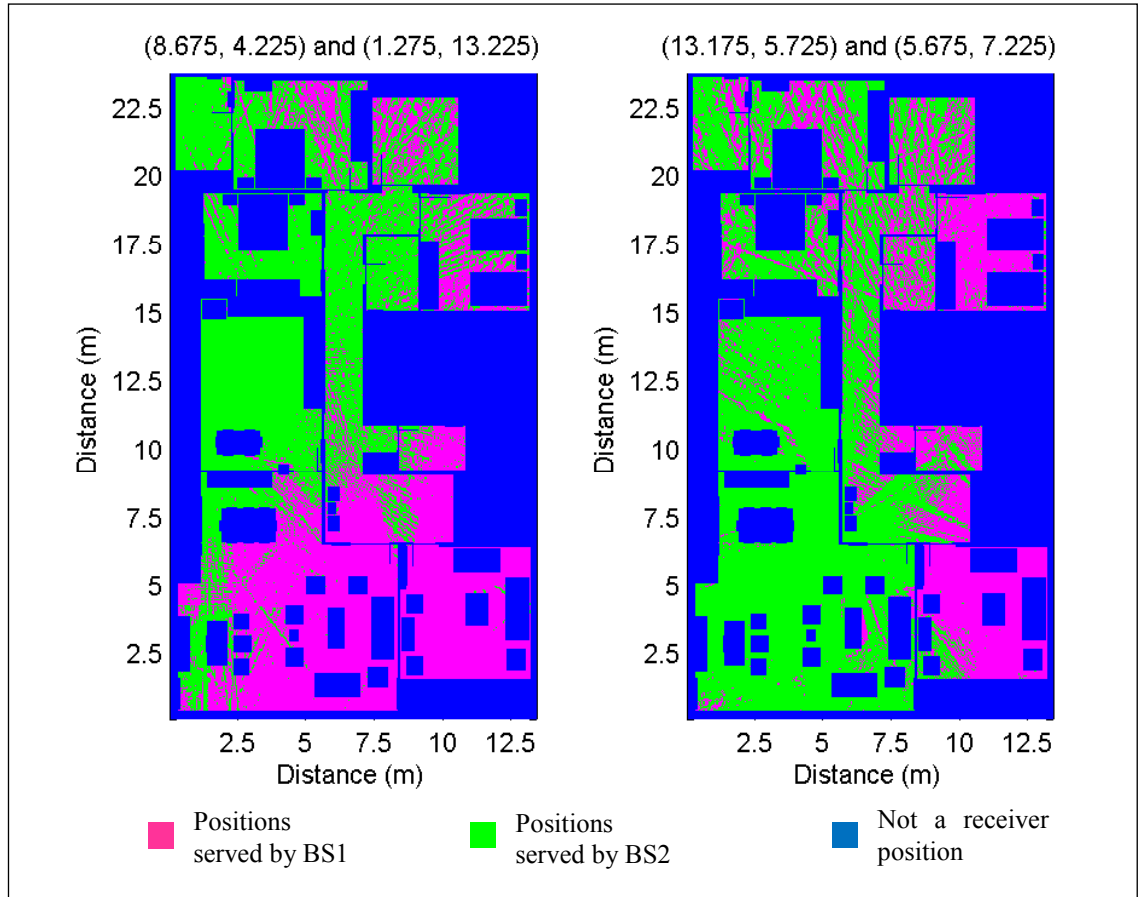


Figure 5.13: Receivers' allocation into the base stations BS1 and BS2 with coordinates (8.675, 4.225) and (1.275, 13.225) respectively, in addition to those with coordinates (13.175, 5.725) and (5.675, 7.225)

As a final point in this section, the environment changes affect the path loss distribution throughout the environment but this may not always lead to a change in the optimal base stations locations. This depends on how severe the change of the path loss distribution is and whether this affects the cost function value such that other positions are those that minimise it. However, if the optimal positions are not affected, the minimal amount of emitted power will definitely change. As an example, consider the closed environment and the environment with people when the trade-off is set to 0 and the priority weights of distribution 2 are used. Different optimal positions are obtained for each environment. In order to check the major cause of the optimal position change, the base stations are placed in the environment with people at (13.175, 5.725) and (5.675, 7.225) which are the optimal positions' coordinates of the closed environment and the path loss distribution over the environment is plotted for both environments in Figure 5.14. It can be seen that the main area affected (circled in red) due to the

presence of people is an area with high priority weights which has affected the cost function value in a way that another combination of base stations' coordinates is able to minimise it.

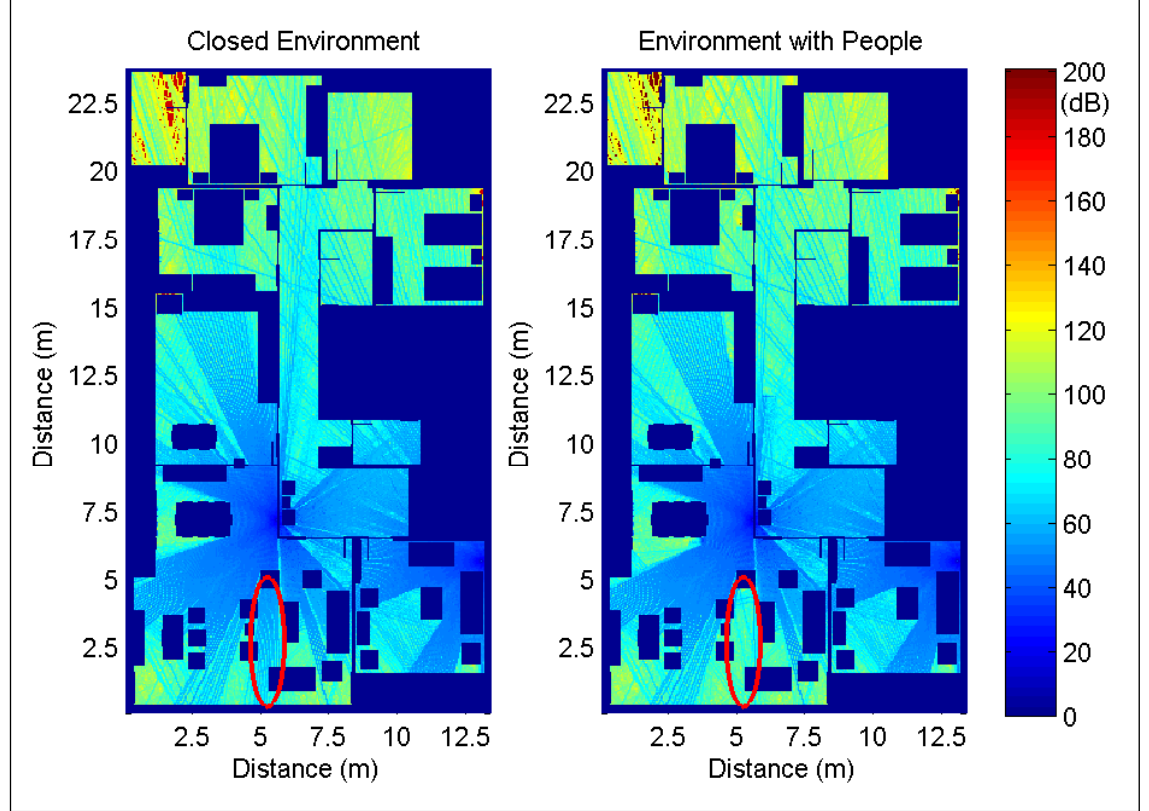


Figure 5.14: Path loss in dB at the possible receivers' positions throughout the closed environment and the environment with people when two base stations are at positions with coordinates (13.175, 5.725) and (5.675, 7.225)

5.5.3 Three Transmitters Scenario

With the intention of decreasing further the amount of power a base station must emit, a third base station is added to contribute to providing service to the indoor environment. The optimisation process is repeated for the three environment configurations. Table 5.3 presents the optimal base stations' coordinates along with the minimal amount of power each base station must emit to provide 80% coverage for trade-off factor values of 0, 0.2, 0.7 and 1 when no priority weights are assigned to the possible receivers' positions as well as when the priority weights are assigned based on distributions 1 and 2 previously shown in Figure 5.5.

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(7.175, 4.225) (7.175, 13.225) (5.675, 19.225) -6.44 dBm	(7.175, 4.225) (7.175, 11.725) (5.675, 19.225) -6.17 dBm	(7.175, 4.225) (4.175, 11.725) (5.675, 19.225) -6.55 dBm	(7.175, 4.225) (4.175, 11.725) (5.675, 19.225) -6.55 dBm
Closed Environment	$W_i=1$	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725) 9.1 dBm	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725) 9.1 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 7.6 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 7.6 dBm
	$W_i=1, 2$ or 3 (D1)	(8.675, 4.225) (1.325, 7.225) (5.675, 19.225) 12.55 dBm	(8.675, 4.225) (1.275, 5.725) (5.675, 16.225) 12.94 dBm	(8.675, 4.225) (5.675, 7.225) (7.175, 19.225) 8.69 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 7.6 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 2.725) (13.175, 5.725) (1.275, 13.225) 22.77 dBm	(5.675, 2.725) (13.175, 5.725) (4.175, 14.725) 17.26 dBm	(8.675, 4.225) (5.675, 7.225) (5.675, 16.225) 11.14 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 7.6 dBm
Open Environment	$W_i=1$	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225) 9.45 dBm	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225) 9.45 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 8.64 dBm	(5.675, 5.725) (4.175, 11.725) (8.675, 19.225) 10.03 dBm
	$W_i=1, 2$ or 3 (D1)	(8.675, 4.225) (1.325, 7.225) (5.675, 19.225) 12.5 dBm	(8.675, 4.225) (1.325, 7.225) (5.675, 19.225) 12.5 dBm	(8.675, 4.225) (5.675, 7.225) (7.175, 19.225) 8.96 dBm	(4.175, 2.725) (7.175, 8.725) (8.675, 19.225) 8.69 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 2.725) (13.175, 5.725) (1.275, 13.225) 23.78 dBm	(4.175, 2.725) (13.175, 5.725) (4.175, 14.725) 18.22 dBm	(8.675, 4.225) (5.675, 7.225) (7.175, 17.725) 9.5 dBm	(8.675, 4.225) (5.675, 7.225) (7.175, 19.225) 8.96 dBm
Environment with People	$W_i=1$	(7.175, 2.725) (1.275, 8.725) (5.675, 19.225) 13.2 dBm	(5.765, 2.725) (7.175, 10.225) (5.675, 20.725) 9.76 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 8.48 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 8.48 dBm
	$W_i=1, 2$ or 3 (D1)	(8.675, 4.225) (1.325, 7.225) (5.675, 19.225) 13.16 dBm	(8.675, 4.225) (1.325, 7.225) (5.675, 19.225) 13.16 dBm	(8.675, 4.225) (4.175, 5.725) (5.675, 16.225) 12.11 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 8.48 dBm
	$W_i=1, 2$ or 3 (D2)	(5.675, 2.725) (13.175, 5.725) (1.275, 13.225) 23.31 dBm	(5.675, 2.725) (13.175, 5.725) (4.175, 14.725) 17.84 dBm	(8.675, 4.225) (4.175, 5.725) (5.675, 16.225) 12.11 dBm	(4.175, 2.725) (7.175, 8.725) (7.175, 19.225) 8.48 dBm

Table 5.3: Optimal base stations' coordinates and minimal amount of emitted power per base station required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty, closed and open environments as well as the environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1 (3 base stations)

It can be noticed from the results shown in Table 5.3 that the addition of furniture to the environment has changed the optimal base stations' positions as well as the minimal amount of emitted power when three base stations are serving the environment. In some cases, one of the base stations does not relocate while the other two do. Among the different optimal locations obtained in the three environment's configurations for the various trade-off factor values when no priority weights are given to the potential receivers' locations, the lowest minimal emitted power is that of the closed environment when the trade-off factor is set to 0.7 or 1. It is 7.6 dBm per base station while it is -6.55 dBm for similar parameters in the empty environment though emitted from different locations. The furnished environment requires then 27 times more power than the empty environment to provide the same coverage percentage equals to 80%.

Furthermore, when no priority weights are assigned to the receivers' positions, the optimal base stations relocate toward areas having the highest path loss as soon as higher priority is given to the standard deviation ($\alpha < 0.5$) seeking to lower the number of receivers' positions having high path loss values.

On the other hand, when higher impact is given to the standard deviation in the cost function definition and as soon as priority weights are assigned to the possible receivers' positions, the base stations move closer to areas enclosing a large number of high priority receivers so that fewer receivers within these areas suffer from high path loss values. The priority weights multiply the path loss values thus the receivers' positions with high priority weights contribute more in the cost function values by increasing it. The higher the path loss values at these locations, the higher the cost function is. In order to minimise the cost function in this case, lower path loss must be present at receivers' locations having high priority weights thus the base stations relocate close to these areas. If higher density priority weights distribution is used, the base stations get even closer to high priority weights areas while the path loss values increase at low priority weights locations. Figure 5.15 shows the path loss distribution over the closed environment when the base stations are at positions that minimise the cost function for a trade-off factor of 0.2 when no priority weights are assigned to the receivers' positions and when priority weights based on distributions 1 and 2 are used. The figure clearly illustrates how the use of priority weights affects the optimal base stations' positions as well the path loss distribution. Before using priority weights, the

base stations were distributed along the environment minimising the receivers' locations with the highest path loss. After including the priority weights based on distribution 1 shown in Figure 5.5, the two base stations serving the centre and the northern parts of the environment moved southward creating an area with high path loss in the northern part of the environment. Using the more condensed priority weights distribution (distribution 2) brings the base stations toward the southern part of the environment where the number of receivers' positions with high priority weights is larger. The area with high path loss values increases further in this case. Concerning the receivers' allocation into the three base stations, when no priority weights are used, the base station at (5.675, 2.725) serves 26.26% of the receivers while these at (7.175, 11.725) and (5.675, 20.725) serve 44.29% and 29.45% respectively. Whereas when priority weights are used, the uppermost base station ((5.675, 16.225) for priority weights distribution 1 and (4.175, 14.725) for priority weights distribution 2) serves around 53% of the receivers' locations while the other two base stations share the remainder. As for the power requirement to cover 80% of the possible receivers' positions, the more the three base stations get close to each other, the more the minimal amount of power increases. The greatest increase in the closed environment occurs when no priority weights are used and when the priority weights of distribution 2 are used for a trade-off factor of 0 where the amount of power is 23.28 times larger in the latter scenario.

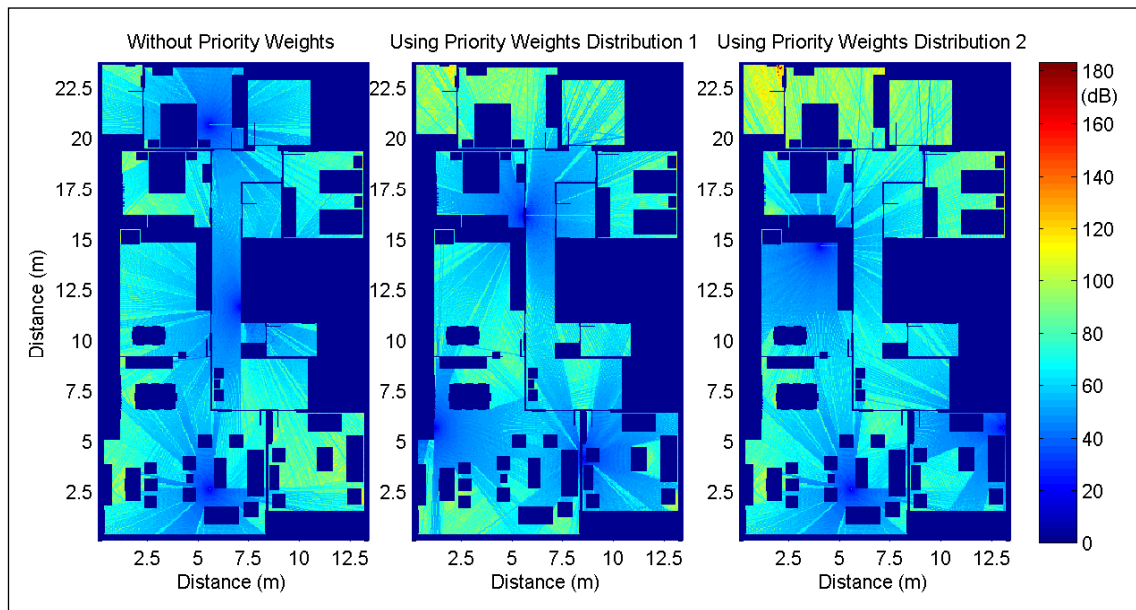


Figure 5.15: Path loss in dB at the possible receivers' positions throughout the closed environment when three transmitters are at their optimal locations when no priority weights are assigned to receivers and when the priority weights of distributions 1 and 2 are used

Compared to the cases when one or two base stations serve the environment, the optimal base stations' positions are more prone to relocate due to the environment changes represented by opening doors and windows and by the addition of people to the environment. That is for lots of the various trade-off factor values and priority weights combinations used, the resulting optimal base stations' locations obtained in the open environment and environment with people differ from these obtained in the closed environment. This depends whether the modification of the path loss values due to the environment changes is able to alter the cost function value in a way that allows another combination of base stations' locations to minimise the cost function or not. The effect of adding people to the environment on the optimal base stations' locations was discussed for the single and two transmitters' scenarios in the previous sections. The same concept applies for the three transmitters' case. In order to explore the effect of opening doors and windows in the environment, the path loss distribution throughout the environment is plotted for both the closed and open environment (Figure 5.16) when the base stations are located at the optimal locations obtained in the closed environment for a trade-off factor of 0.7 when the priority weights of distribution 2 are assigned to the possible receivers' positions. The corresponding coordinates are (8.675, 4.225), (5.675, 7.225) and (5.675, 16.225). Based on Figure 5.16, the most visible changes occurred in the northern part of the environment as the base station at (5.675, 16.225) is the closest to one of the doors that is opened. To clearly see the path loss values change, the difference between the path loss values in the closed environment and these in the open environment are shown in Figure 5.17 where a negative difference means the path loss has deteriorated (increased) after opening the doors and windows. The path loss values are affected all over the environment but the area that is highly affected is the one in the northern part of the environment. Consequently, the optimal base stations' locations have changed after the environment change. The base station located in the northern part of the environment is pushed northward to (7.175, 17.725) while the other two base stations are still at the same locations with coordinates (8.675, 4.225) and (5.675, 7.225). Note that as the base station moved northward, the path loss values in the northern part of the environment decrease, thus the minimal amount of power required to cover 80% of the environment is lower in the open environment compared to that in the closed environment where the values are 9.5 dBm and 11.14 dBm respectively.

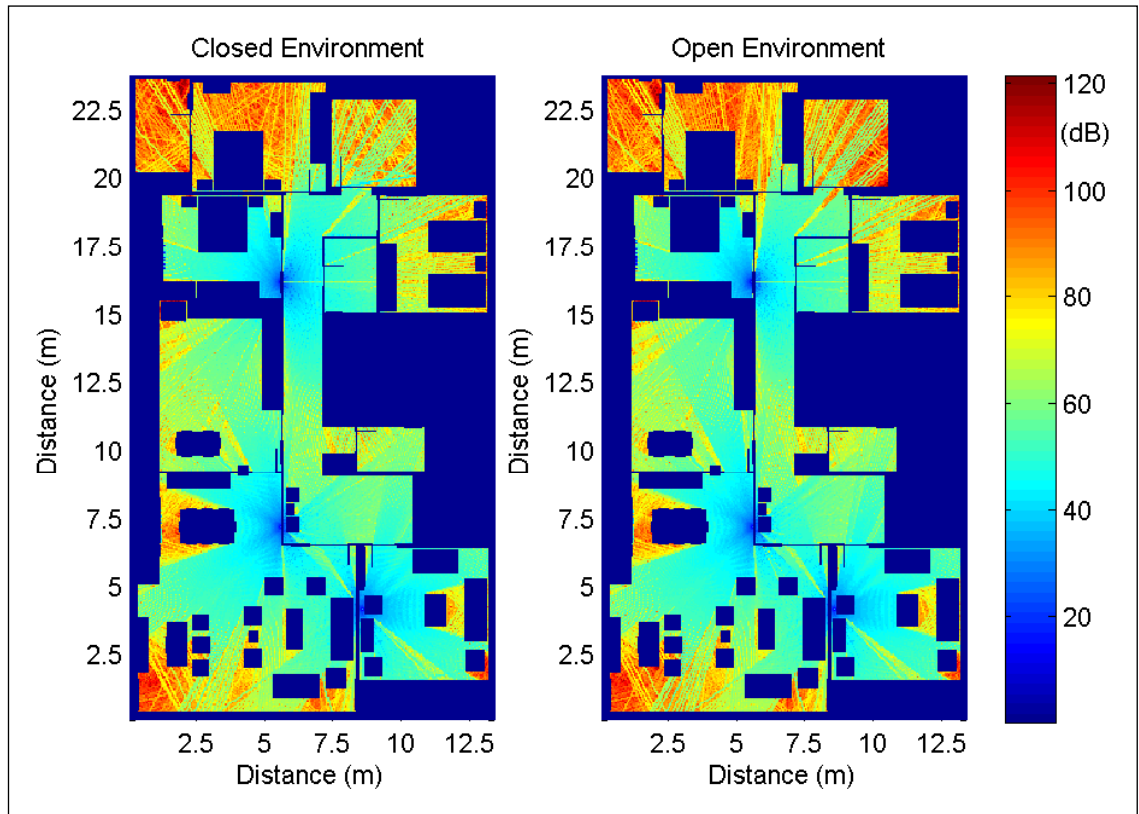


Figure 5.16: Path loss in dB at the possible receivers' positions throughout the closed and open environments when three base stations are at positions with coordinates (8.675, 4.225), (5.675, 7.225) and (5.675, 16.225)

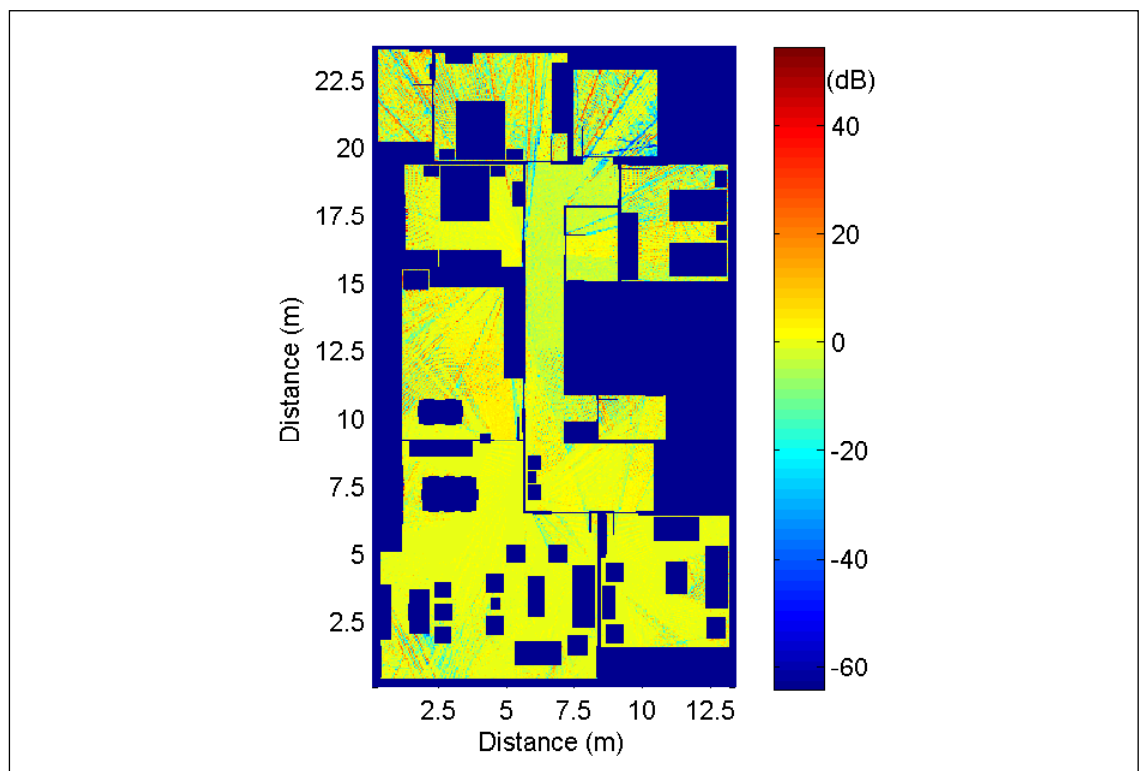


Figure 5.17: Difference between the path loss values of the closed and open environments when three base stations are at positions with coordinates (8.675, 4.225), (5.675, 7.225) and (5.675, 16.225)

On the other hand, the use of three transmitters as opposed to one or two transmitters decreases the total power requirement for all the trade-off factor values and priority weights combinations for the different environment's configurations. For example, consider the latest discussed scenario where the open environment is examined and the cost function parameters are 0.7 for the trade-off factor in addition to priority weights assigned based on distribution 2. The total power when three transmitters are positioned based on the optimal locations is around 101 times and 2.35 times less than that when one or two transmitters are serving the environment respectively.

5.6 The Effect of Coverage Percentage Selection On The Minimal Power

All the power level values previously found in this chapter correspond to 80% coverage. Once the desired coverage percentage is decreased, the minimal amount of emitted power will decrease. The reduction ratio varies depending on the base station's location. As an example, the closed environment is selected and the minimal amount of power required to cover 70% of the environment is found, assuming that the receiver's sensitivity is -65 dBm, when one, two or three base stations are positioned at their optimal locations obtained for a trade-off factor of 0.2 when no priority weights are assigned to the possible receivers' locations (refer to Table 5.1, Table 5.2 and Table 5.3). Table 5.4 shows the power levels each base station must emit to provide service to 70% and 80% of the receivers' locations. The 10% decrease in the desired coverage is able to decrease the power requirement 4.21, 3.4 and 3.5 times when the environment is served by one, two and three base stations respectively. Note that the power reduction depends on the base stations locations.

	70% Coverage	80% Coverage
1 Base Station	24.41 dBm	30.66 dBm
2 Base Stations	10.01 dBm	15.33 dBm
3 Base Stations	3.56 dBm	9.1 dBm

Table 5.4: Minimal amount of emitted power by each base station when the environment is served by 1, 2 or 3 base stations for a receiver's sensitivity of -65 dBm

5.7 Optimisation Using The Genetic Algorithm

Throughout this work, brute force optimisation is used as it is preferred over algorithmic optimisation due to the fact that there are multiple sub-optimal solutions. Figure 5.18 shows the cost function (equation 5.1) distribution in the closed environment when no priority weights are assigned to the possible receivers' locations with the trade-off factor set to 0.2 for the 81 possible transmitter's positions. It can be seen that some transmitter locations have close cost function values hence the cost function has multiple local minimums. For this reason, if algorithmic optimisation is used, sub-optimal solution is likely to be obtained. As one of the objectives of this work is to show the effect of environment changes on the optimal base station's locations, an exact solution needs to be obtained.

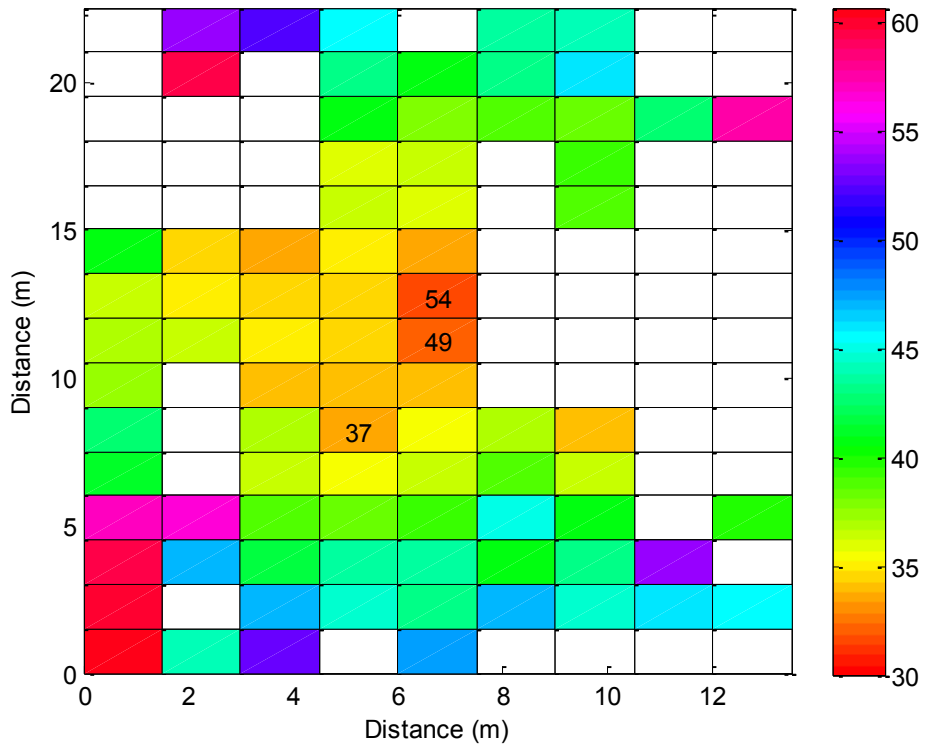


Figure 5.18: Cost function values for the 81 possible transmitter's locations in the closed environment when no priority weights are assigned to the possible receivers' locations with the trade-off factor value set to 0.2

The minimum of the cost function values shown in Figure 5.18 is found using genetic algorithm and every time the optimisation is repeated, different optimal location is obtained. Therefore, the optimisation process must be repeated multiple times and the

most probable base station location must be the one with the lowest cost function value and is the one to be considered the minimum. As an example, the optimisation is repeated 200 times and the histogram of the optimal location number and that of the cost function values at the obtained optimal locations are shown in Figure 5.19 and Figure 5.20. It can be seen that the exact optimal location number 54, marked on Figure 5.18, is the one that occurred the most while repeating the optimisation using the genetic algorithm. The second two most probable locations (49 and 37) have their corresponding cost function values close to the optimal one and they are also marked on Figure 5.18. Note that the other less probable locations obtained have a cost function value that is higher than that of the optimal one by a value of 2. In this case, instead of performing the optimisation 200 times, brute force optimisation can be used and for this environment, it takes 0.062 seconds to calculate the cost function for one transmitter location or a total of 5.022 seconds to evaluate it for all the possible transmitter's locations (81 locations). If two transmitters are assumed to serve the environment, 0.078 seconds are needed to evaluate the cost function for one combination of two transmitters or a total of 4.212 minutes for the 3240 possible combination. Adding a third transmitter increases the total required time to 133.668 minutes and this is still affordable. On the other hand, if four transmitters are used, the total time required to calculate the cost function for all the possible combinations of four transmitters will be 43.4421 hours assuming that each cost function value calculation will take the same amount of time needed when three transmitters are assumed to serve the environment (0.094 seconds) although it will be slightly higher. Note that the computation times are calculated when a personal laptop is used. Consequently, as the number of base stations increases and multiple transmitters are assumed to serve the environment, brute force optimisation will become time consuming and sometimes not applicable, hence algorithmic optimisation will be required though it will end up with sub-optimal solution. If a supercomputer was used, the simulations would have been faster and brute force optimisation can be applicable up to a larger number of transmitters.

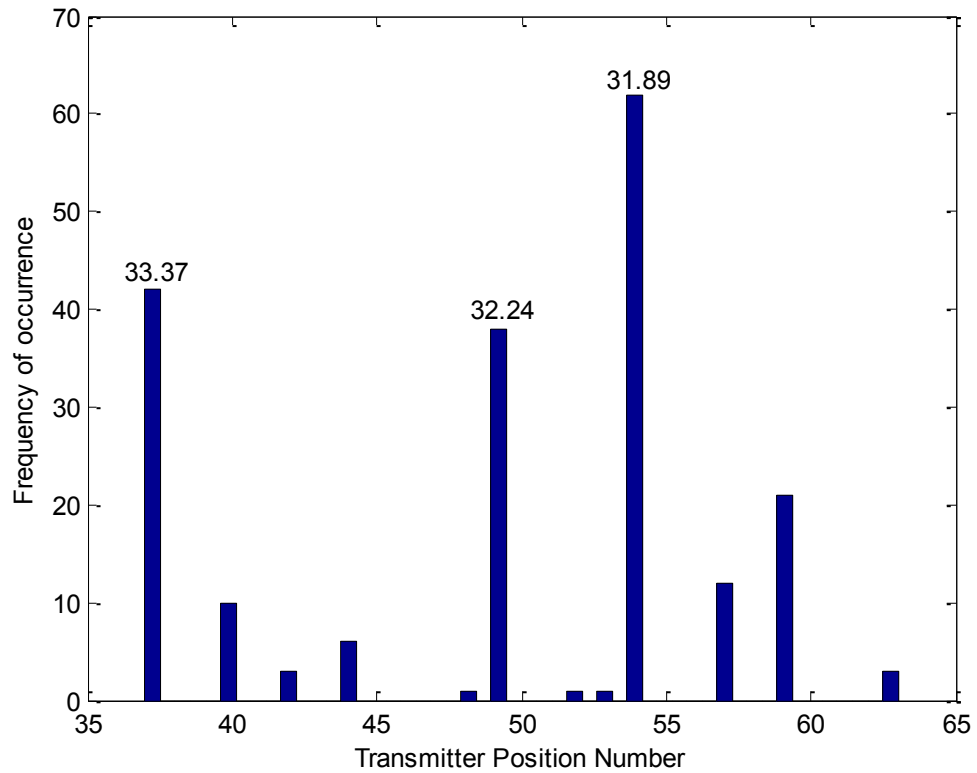


Figure 5.19: Histogram of optimal transmitter location's numbers obtained after running the genetic algorithm 200 times in the closed environment when no priority weights are assigned to the possible receivers' locations with the trade-off factor set to 0.2

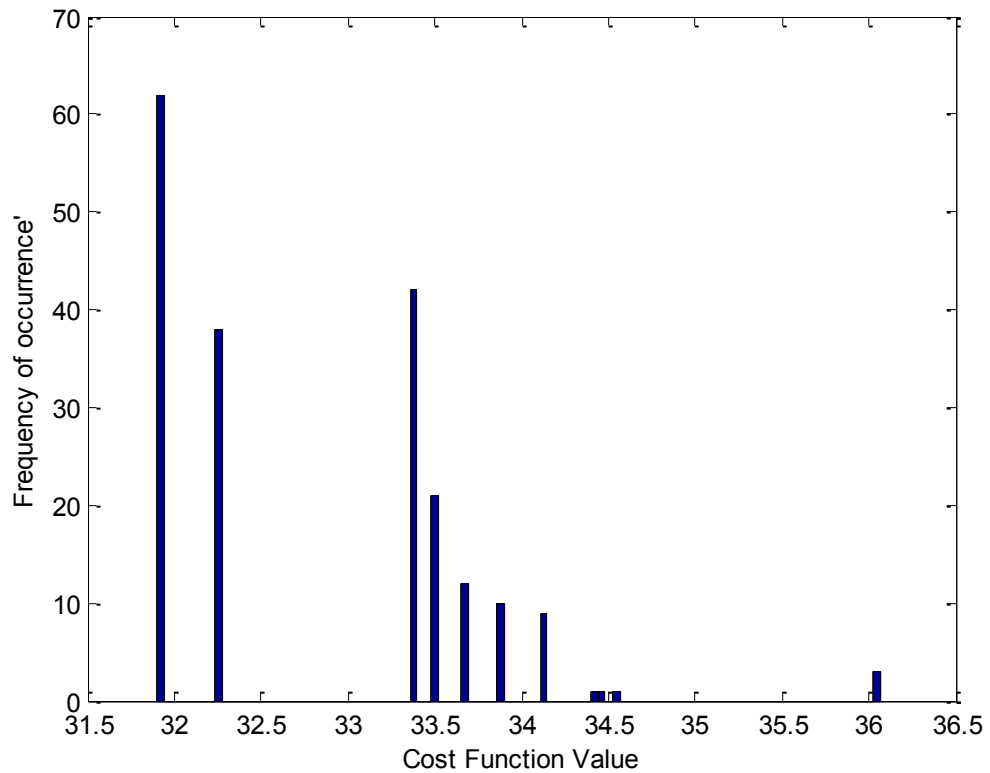


Figure 5.20: Histogram of the cost function values obtained after running the genetic algorithm 200 times in the closed environment when no priority weights are assigned to the possible receivers' locations with the trade-off factor set to 0.2

5.8 The Effect of The Cut-off Power Level on The optimal Transmitters' Positions

One of the ray tracing software parameters that needs to be specified is the cut-off power level. This parameter represents the value below which the software stops tracing a ray (refer to section 4.4.1). In order to examine the effect of the selection of this parameter on the optimal base stations' locations, the cost function of equation 5.1 as well as its variation, after assigning priority weights to the possible receivers' locations (equation 5.2), are minimised based on the path loss values of the closed environment. Two cut-off levels are selected: -60 dB and -90 dB. Table 5.5 and Table 5.6 show the optimal base station's coordinates obtained after minimising the cost function with and without the use of priority weights for different cut-off power levels and different trade-off factor values. It can be observed that the optimal base station's coordinates are more sensitive to the cut-off power level change when priority weights are assigned to the possible receivers' locations. In other words, the optimal base station's locations for the two cut-off power levels are the same except when the trade-off factor is set to 1 when no priority weights are assigned to the possible base receivers' positions whereas the reverse happened when priority weights are taken into consideration. When no priority weights are assigned to the possible receivers' locations, a position in the centre of the environment is obtained and a change in the cut-off power level hardly affects it. When the cut-off level is reduced, a ray is traced longer and it will result in lower path loss values with some locations affected more than others, mainly those that were initially not receiving any ray. Consequently, when priority weights are assigned to the possible receivers' locations, they will scale the path loss values and affect the cost function values so that its minimum varies especially when low trade-off factor values are used and higher importance is given to minimising the number of receivers' positions with the highest path loss values.

Cut-off Level	$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
-60 dB	(7.175, 13.225)	(7.175, 13.225)	(7.175, 13.225)	(7.175, 13.225)
-90 dB	(7.175, 13.225)	(7.175, 13.225)	(7.175, 13.225)	(7.175, 11.725)

Table 5.5: Optimal base station's coordinates in the closed environment when no priority weights are assigned to the possible receivers' locations for cut-off power levels of -60 dB and -90 dB with trade-off factor values of 0, 0.2, 0.7 and 1

Cut-off Level	$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
-60 dB	(7.175, 5.725)	(7.175, 8.725)	(7.175, 8.725)	(7.175, 11.725)
-90 dB	(5.675, 7.225)	(10.175, 8.725)	(7.175, 11.725)	(7.175, 11.725)

Table 5.6: Optimal base station's coordinates in the closed environment when the priority weights of distribution 1 are assigned to the possible receivers' locations for cut-off power levels of -60 dB and -90 dB with trade-off factor values of 0, 0.2, 0.7 and 1

The same process is repeated when two base stations are assumed to serve the environment and the optimal positions' coordinates are shown in Table 5.7 and Table 5.8. It can be noticed that whether priority weights are assigned to the possible receivers' locations or not, the optimal base stations' coordinates changed when low trade-off factor values are used and higher priority is given to the standard deviation. Consequently, the cut-off power level selection affects the optimal base stations' locations although the -90 dB is preferred as discussed in section 4.4.1.

Cut-off Level	$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
-60 dB	(5.675, 4.225) (5.675, 16.225)	(5.675, 5.725) (5.675, 16.225)	(5.675, 5.725) (7.175, 19.225)	(5.675, 5.725) (7.175, 19.225)
-90 dB	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (7.175, 19.225)	(5.675, 5.725) (7.175, 19.225)

Table 5.7: Optimal base station's coordinates in the closed environment when no priority weights are assigned to the possible receivers' locations for cut-off power levels of -60 dB and -90 dB with trade-off factor values of 0, 0.2, 0.7 and 1 (2 base stations)

Cut-off Level	$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
-60 dB	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (7.175, 19.225)	(5.675, 5.725) (7.175, 19.225)
-90 dB	(13.175, 5.725) (5.675, 7.225)	(5.675, 5.725) (5.675, 16.225)	(5.675, 5.725) (7.175, 19.225)	(5.675, 5.725) (7.175, 19.225)

Table 5.8: Optimal base station's coordinates in the closed environment when the priority weights of distribution 1 are assigned to the possible receivers' locations for cut-off power levels of -60 dB and -90 dB with trade-off factor values of 0, 0.2, 0.7 and 1 (2 base stations)

5.9 The Effect of Antenna Polarisation on The Cost Function Values

Another parameter that the software requires is the antenna polarisation. Throughout this work the polarisation is mainly selected to be parallel due to simulation time restrictions as discussed in section 4.4.2. This section will discuss the effect of the polarisation selection on the cost function values. The environment is considered with open doors and windows. Fourteen possible transmitter locations are selected as specified in Figure 5.21 with the positions where a transmitter cannot exist marked in dark blue and the path loss distribution is obtained to calculate the cost function values for both the parallel and perpendicular polarisations for different priority weights and trade-off factor values. Figure 5.22 and Figure 5.23 show the cost function values when all the priority weights are set to 1 and when they are set to 1, 2 or 3 based on distribution 1 (Figure 5.5). It can be noticed that the cost function values of the parallel and perpendicular polarisation vary based on the same trends with those of the parallel polarisation being higher due to the fact that perpendicular polarisation results higher field strength values (or lower path loss values) as discussed in section 4.4.2. Consequently, the polarisation selection will not affect the optimal base station's locations.

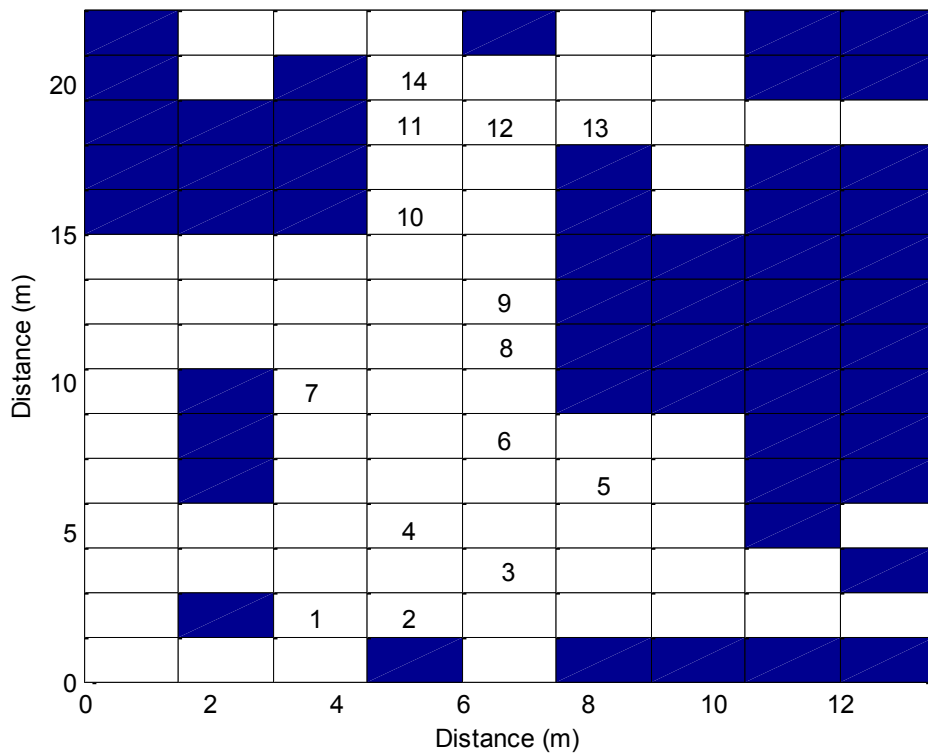


Figure 5.21: The 14 transmitter locations distribution throughout the open environment with the positions where a transmitter cannot exist marked in dark blue

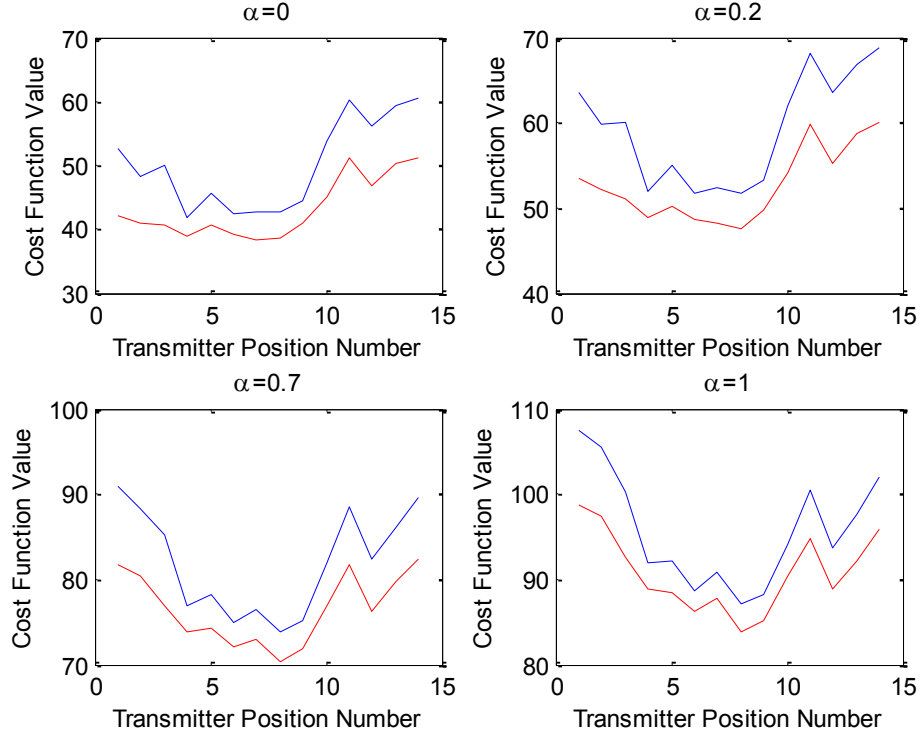


Figure 5.22: Cost function values for 14 transmitter locations for the open environment when the priority weights of distribution 1 are assigned to the possible receivers' locations for trade-off factor values of 0, 0.2, 0.7 and 1 with the blue and red colours corresponding to the parallel and perpendicular polarisations respectively

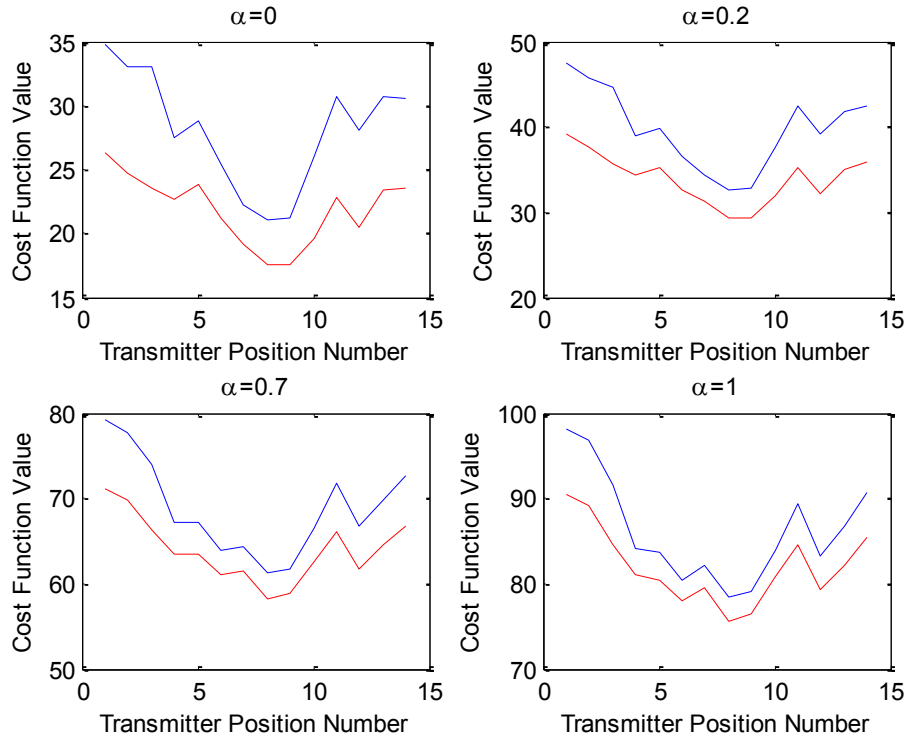


Figure 5.23: Cost function values for 14 transmitter locations for the open environment when no priority weights are assigned to the possible receivers' locations for trade-off factor values of 0, 0.2, 0.7 and 1 with the blue and red colours corresponding to the parallel and perpendicular polarisations respectively

5.10 Comparison of The Cost Function With A Cost Function in The Literature

In order to check the performance of the cost function used in this chapter, the cost functions defined in [43] and [44] and previously discussed in chapter 3 are minimised and the optimal base stations' coordinates are compared. Recall from chapter 3 that the two cost functions are similar and just differ by which parts are combined together before being multiplied by the trade-off factor that specifies which part of the cost function must influence the optimisation more. They are composed of the path loss weighted average and the weighted average of the path loss values of positions with a path loss higher than a given threshold, in addition to the weighted path loss of the worst receiver's location so that it has satisfactory service. Penalty factors are used for the receivers' positions having a path loss lower than the threshold. Consequently, the concept of these cost functions is close to that defined in equations 5.1 and 5.2. They minimise the overall path loss values throughout the environment while taking care of the receivers' positions with high path loss, but in a different way. They try to reduce the path loss for receivers' positions violating the path loss threshold below which the service is considered good and that of the poorest location.

Two approaches can be used for this comparison. The environments defined in these papers can be reproduced using the ray tracing software in order to get the path loss values and then use them to calculate the values of the cost function of equation 5.2 and compare the results with those that appear in the papers. The problem with this approach is that there was lack of information regarding the dimensions of the environment as the map is not to scale. The second issue is that neither the receivers' locations nor the priority weights and penalty factors are specified. However, there was a case in [43] where all the priority weights are set to 1 and a figure sparsely shows the base stations' locations when the environment is served by five base stations. After approximating the dimensions of the environment, it was mapped into the drawing tool of the ray tracing software with walls being the only modelled constituent. The genetic algorithm was then used to optimise the cost function of equation 5.2 when the priority weights are set to 1 with a trade-off factor equal to 0.7.

Based on the discussion of section 5.7, the cost function modelling the base station's location problem has multiple local minimums; hence, algorithmic

optimisation will lead to a sub-optimal solution. On the other hand, algorithmic optimisation is used in the papers meaning that the solutions presented are sub-optimal solutions too. Adding this to the lack of information, it was impossible to reach the same optimal solutions; however, a visually close solution is obtained. After running the genetic algorithm 200 times, the histogram of the solutions is obtained. Figure 5.24 shows the path loss distribution obtained when the five base stations are located based on the most probable sub-optimal solution with positions where a receiver cannot exist shown in blue. Another sub-optimal solution that looks closer to that presented in Fig.2 in [43] is shown in Figure 5.25.

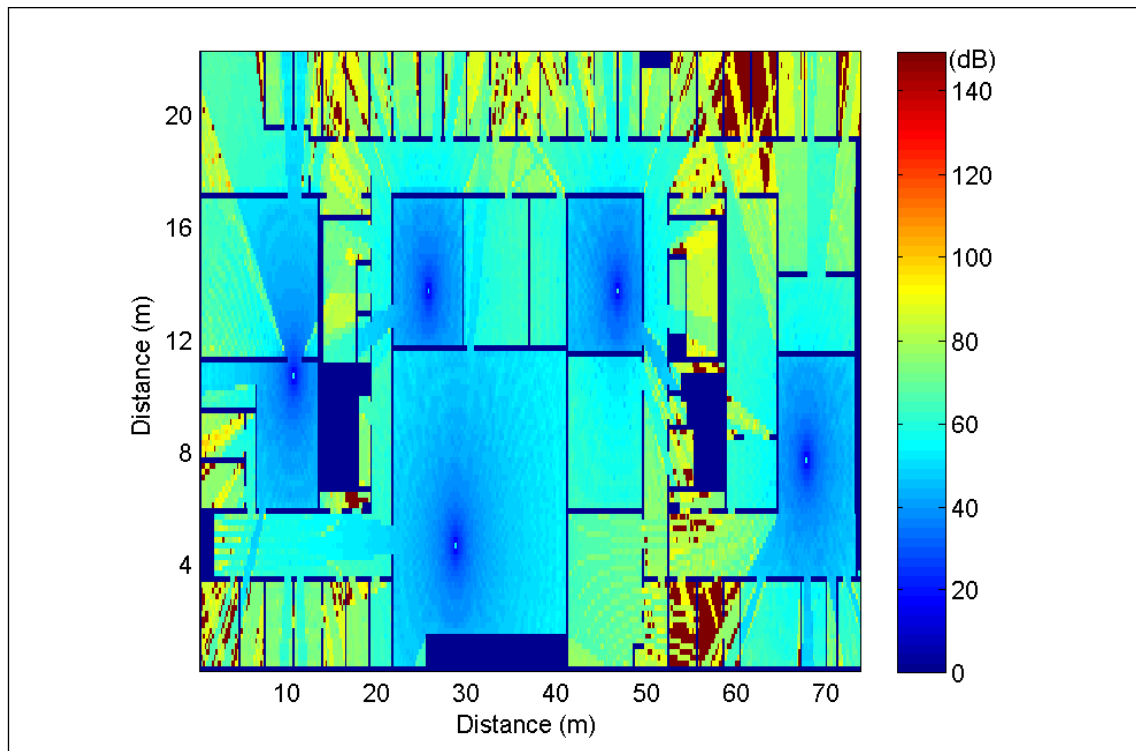


Figure 5.24: Path loss in dB at the possible receivers' positions throughout environment when five base stations are serving the environment

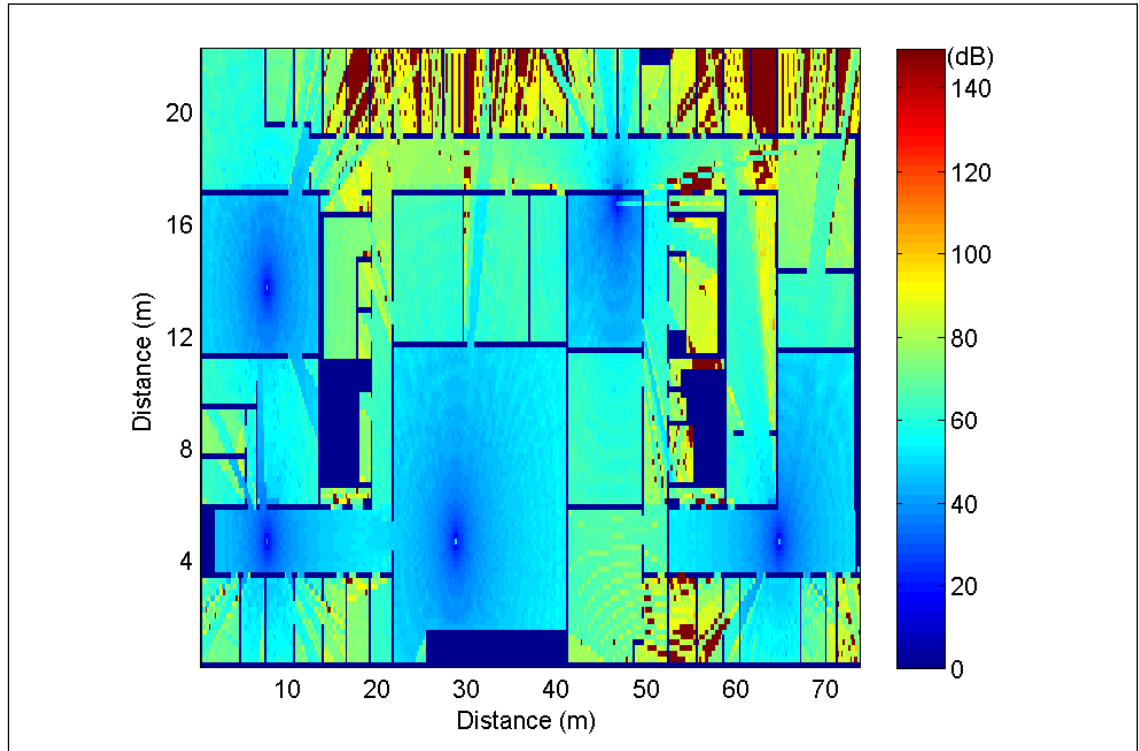


Figure 5.25: Path loss in dB at the possible receivers' positions throughout environment when five base stations are serving the environment and located at different sub-optimal locations compared to Figure 5.24

As for the second approach, it is to use the cost functions defined in the papers to find the optimal base station's locations of the test environment defined in chapter 4 and compare them with those obtained when the cost function of equation 5.2 is used. The cost function of [44] was then tested on the different environment's configurations when they are served by one, two or three base stations. When a high trade-off factor is used for both cost functions, the optimal base stations' locations are equal or very close. However, when low trade-off factor values are used, the threshold path loss selection becomes more critical and its value highly affects the optimal base stations' locations and can sometimes lead to distant optimal positions when comparing the optimal positions obtained by both cost functions. Note that when multiple transmitters are used, the overall system performance is increased thus lower path loss thresholds must be selected.

For example, the empty environment is considered where no priority weights neither penalty factors are assigned to the possible receivers' locations. If a single base station serves the environment and the path loss threshold is set to 100 dB, setting the

trade-off factor of the cost function of equation 5.1 to 0.7 and that of the second equation to 0.9 leads to the same optimal position whereas if both of them are 0.7 or 0.2 the optimal base station's locations are one step diagonally adjacent keeping in mind that the transmitter's positions are selected based on a $1.5 \text{ m} \times 1.5 \text{ m}$ grid as discussed in chapter 4. When two transmitters are serving the empty environment and using the same trade-off factor of 0.7 for both cost functions with a path loss threshold of 90 dB or 60 dB, the same optimal base stations' coordinates are obtained. However, when the trade-off is lowered to 0.2, the optimal base stations' positions are adjacent. The coordinates obtained after minimising the cost function of equation 5.1 are (7.175, 5.725) and (5.675, 19.225) while those obtained after minimising the cost function of [44] are (7.175, 4.225) and (4.175, 19.225) thus, the first base station has moved one position eastward and the second has moved one position southward. When the base stations are at (7.175, 5.725) and (5.675, 19.225), the coverage is 71.38% and 99.7% for threshold of 60 dB and 90 dB respectively whereas the positions (7.175, 4.225) and (4.175, 19.225) provide 70.97% and 99.65% for the same thresholds (60 dB and 90 dB). In this case, the optimal positions obtained based on equation 5.1 provide slightly higher coverage. In addition, when three base stations serve the environment with the threshold path loss equal to 80 dB and for trade-off factor equal to 0.7 for both functions, two of the base stations are exactly at the same locations while the third moved one cell eastward. As for the coverage, it is 98.89% and 98.8% when the base stations are positioned based on the optimisation of equation 5.1 and the equation defined in [44] respectively. Whereas, when the trade-off is decreased to 0.2, comparing the optimal positions obtained for the two cost functions, two of the base stations move two cells westward while the third is far away. The coverage percentages are 99.23% and 90.86% when the base stations are positioned based on the optimisation of equation 5.1 and the equation defined in [44] respectively thus the positions obtained based on equation 5.1 led to higher coverage. It is expected that for low trade-off factor values, the cost functions will lead to different results as each treats the high path loss receivers' positions in a different way, however, the path loss threshold can be adjusted to get the optimal positions somewhat close. The same observations apply for the different environment's configurations as well as when priority weights are assigned to the possible receivers' positions although penalty factors are always assumed to be unity.

5.11 Conclusions

In this chapter, the problem of finding the best base station's position in an indoor environment was modelled as an optimisation problem where a cost function was defined based on the path loss values. The cost function consists of both the average and the standard deviation of the path loss values where a trade-off factor is used to specify whether the average or the standard deviation must contribute more in the cost function values. The optimisation of this cost function minimises the overall path loss values throughout the indoor environment while reducing the number of receivers' positions having the highest path loss values. The optimal results of the cost function were compared with those obtained based on a cost function previously defined in literature and they closely match.

In the empty environment, when higher priority is given to the standard deviation, the optimal base station's position is located in the centre of the environment so that the number of receivers' locations having high path loss values is reduced mainly at both ends of the environment. As the trade-off factor is increased, higher priority is given to the average. In this case, the base station relocates in a way that increases the area of low path loss values so that the average path loss is minimised causing more receivers' positions with high path loss. Whereas, when multiple base stations serve the environment, the effect of lowering the trade-off factor is the movement of the base stations toward the sides of the environment to decrease the path loss values there. The more the trade-off factor is reduced, the more the base stations get closer to areas with high path loss in order to decrease the number of receivers' positions with the highest path loss.

After finding the optimal base stations' positions, the minimal amount of power required to provide a predefined coverage was found. The higher the desired coverage percentage is, the higher the minimal emitter power is. Furthermore, it was shown that the use of multiple base stations highly reduces the total amount of power required which lowers the power consumption as well as the interference with neighbour environments.

On the other hand, furniture is added to the environment and three different scenarios of the furnished environment were considered. The first one is when all windows and doors are closed, the second when all windows and almost all the doors

are open and the last one contains people. It was shown that the addition of furniture to the environment highly increases the path loss values throughout the environment, thus supplementary power is required to keep the same coverage in a furnished environment compared to that in an empty environment. For the same base stations' positions, the environment with people requires the highest amount of power compared to the closed and open environments.

It has been shown that the optimal base stations' positions are sensitive to environment changes. Thus, when the different environment's configurations are considered, different optimal base stations locations are obtained though not for all the cost functions parameters' combinations. The closer a base station is to a change in the environment, the higher the effect is on the path loss values hence the probability that the base station will relocate is higher.

In addition, once an environment is furnished, one can estimate the areas where a receiver is more likely to settle, thus priority weights are assigned to the possible receivers' locations. The inclusion of priority weights in the cost function definition affects the optimal base stations' locations. For low trade-off factor values, the base stations get very close to areas containing the highest number of receivers' positions with high priority. This will increase the path loss values within low priority receivers' areas and more emitted power is required to keep the same coverage percentage. In addition, when multiple base stations are used, the receivers' allocation among the base stations may be unbalanced. The optimal base stations' positions gradually move away as the trade-off factor is increased. The less the priority weights distribution is condensed, the farther the base station moves toward the centre of the environment while increasing the trade-off factor.

As for the trade-off factor selection, it depends on the path loss threshold above which a receiver's position does not have service as well as if priority weights are assigned to the possible receivers' locations or not. When no priority weights are used and when the path loss threshold is high, a low trade-off factor is recommended ($\alpha < 0.5$) and this leads to higher coverage. When the path loss threshold is low, higher importance must be given to the average path loss ($\alpha > 0.5$) to get higher coverage. On the other hand, when priority weights are assigned to the possible receivers' locations, higher overall coverage is achieved for trade-off values higher than 0.5 but with lower

coverage at higher priority weights receivers' locations. Using low trade-off values, lead to higher coverage at high priority locations but lower overall coverage. Consequently the selection of the trade-off values depends on what one needs to achieve in terms of covered locations.

Chapter 6: Optimising the Base Stations' Positions based on Rms Delay Spread and Path Loss values

6.1 Introduction

The optimal base stations' positions have always been selected based on the signal level although in different forms such as minimising the path loss, maximising the field strength or the coverage area. However, sufficient signal level reaching a device does not always mean reliable communication. The time dispersion parameters such as the mean excess delay or root-mean-square (rms) delay spread must be taken into consideration. If the rms delay spread gets larger than the symbol rate, inter-symbol interference occurs [1] and the service deteriorates. Therefore, a receiver getting sufficient power level with high delay spread will not have reliable service. The higher the symbol rate is, the lower the critical delay spread value is. As indoor wireless systems are evolving, greater bit rates are achieved. This means that the time dispersion parameters cannot be ignored anymore while looking for the best base stations' positions.

Chapters 3 and 5 discussed the optimisation of base stations' locations based on signal level with various forms. In this chapter, three different forms of objective functions that take into account both the path loss and the rms delay spread will be defined and optimised. The same strategy adopted in chapter 5 will be respected: the indoor environment will be first considered empty throughout this chapter as it is most likely that the base stations' positions will be selected before any knowledge of the furniture location. Different cost functions' parameters will be considered and their effect on the optimal locations will be discussed for single and multiple transmitters' scenarios. The environment dynamics will be then studied in chapter 7 where the environment will be considered in different circumstances. Note that when multiple base stations serve the environment, the co-channel interference was neglected due to the fact that within the 2.4 GHz range, three non-overlapping channels can be used and that is the maximum number of base stations used.

6.2 Path Loss and Root-Mean-Square Delay Spread Cost Functions Definition

In order for a user to be served by a base station, high signal level must be reaching the receiver with a low rms delay spread. The amount of signal level that a receiver must obtain is related to the receiver's sensitivity while the maximum acceptable rms delay spread is related to the symbol rate. A receiver's location is considered to enjoy guaranteed service if it has the path loss and the rms delay spread less than predefined threshold values. The threshold values are specified based on the receiver's sensitivity and the symbol rate. Different ways of expressing the objective function based on path loss and rms delay spread values are defined in this section.

The first objective function maximises the number of receivers' positions having the path loss and the rms delay spread lower than predefined threshold values. It is then expressed as follows:

$$f = \frac{1}{N} \sum_{i=1}^N C_i \quad (6.1)$$

$$C_i = \begin{cases} 1 & \text{when } PL_i < PL_{th} \text{ and } DL_i < DL_{th} \\ 0 & \text{otherwise} \end{cases} \quad (6.2)$$

where N is the number of possible receivers' locations, PL_i and DL_i are the path loss and the rms delay spread at the i^{th} receiver's location and PL_{th} and DL_{th} are the path loss and rms delay spread thresholds respectively. Maximising this cost function over all the possible transmitter's locations maximises the number of receivers' locations enjoying guaranteed service.

On the other hand, receiving enough field strength (a path loss lower than the threshold value) with an rms delay spread higher than the threshold value does not totally mean losing the service. The higher the rms delay spread goes above the threshold value, the higher the error rate will be in the received signal which means the service will be poorer. However, having a low field strength (a path loss higher than the threshold value) with an rms delay spread that is lower than the threshold value definitely means that the receiver does not have service. Taking this into consideration, a variation of the previously defined objective function is suggested. It is defined as follows:

$$f = \frac{1}{N} \sum_{i=1}^N C_i \quad (6.3)$$

$$C_i = \begin{cases} 1 & \text{when } PL_i < PL_{th} \text{ and } DL_i < DL_{th} \\ 0.5 & \text{when } PL_i < PL_{th} \text{ and } DL_i > DL_{th} \\ 0 & \text{otherwise} \end{cases} \quad (6.4)$$

where N is the number of possible receivers' locations, PL_i and DL_i are the path loss and the rms delay spread at the i^{th} receiver's location and PL_{th} and DL_{th} are the path loss and the rms delay spread thresholds respectively. Maximising this cost function over all the possible transmitter's locations maximises the number of receivers' locations enjoying a guaranteed service as well as the positions with risky service or in other words these with lower quality service.

Another way of expressing the objective function while considering both the path loss and the rms delay spread is to split the function into two parts. Each part takes into consideration one of the criteria (path loss or the rms delay spread). In other words, the first part will count the receivers' positions with path loss less than the threshold path loss while the second part will count the receivers' positions with rms delay spread less than its threshold value. A trade-off factor is used in order to specify which part of the function should have higher influence on the objective function. The expression of the third objective function is as follows:

$$f = \alpha \frac{1}{N} \sum_{i=1}^N q_i + (1 - \alpha) \frac{1}{N} \sum_{i=1}^N p_i \quad (6.5)$$

$$q_i = \begin{cases} 1 & \text{when } PL_i < PL_{th} \\ 0 & \text{otherwise} \end{cases} \quad (6.6)$$

$$p_i = \begin{cases} 1 & \text{when } DL_i < DL_{th} \\ 0 & \text{otherwise} \end{cases} \quad (6.7)$$

where α is the trade-off factor defined to be between 0 and 1, N is the number of possible receivers' locations, PL_i and DL_i are the path loss and the rms delay spread at the i^{th} receiver's location and PL_{th} and DL_{th} are the path loss and the rms delay spread thresholds respectively. When the trade-off factor is set to 0, the cost function becomes dependent on the rms delay spread values only whereas when it is set to 1, the cost function depends on the path loss values only. For any other trade-off factor value, the cost function depends on both the rms delay spread and the path loss where a trade-off

factor value less than 0.5 means higher importance is given to the rms delay spread values and a trade-off factor value greater than 0.5 means higher importance is given to the path loss values.

For all the objective functions defined in this section, when multiple transmitters are used, the receiver is assumed to be served by the base station providing the lowest path loss and the corresponding rms delay spread is used. In addition, the maximisation will be done over all the possible transmitters' locations combinations.

6.3 Single Transmitter's Location Optimisation Results For The Empty Environment

The environment defined in chapter 4 is considered empty throughout this chapter as it is most likely that the base stations' locations will be selected at the design stage before any knowledge of the furniture items and locations. It will be initially assumed to be served by a single base station.

The three cost functions previously defined in this chapter are optimised over all the possible transmitter's positions. Different combinations of threshold values for both the path loss and rms delay spread were considered. In this section, four possible combinations will be presented. The two path loss threshold values that were selected are -90 dB and -60 dB. Knowing that the transmitter modelled in the software emits a power of 15 dBm, the receiver's sensitivities corresponding to the selected path loss thresholds are then -75 dBm and -45 dBm respectively. As for the rms delay spread, the selected threshold values are 400 ns and 30 ns. Based on equation 2.5 and the selected rms delay spread threshold values, the maximum symbol rate that can be used without having inter-symbol interference is 250 KSymbol/s for the 400 ns value and 3.33 MSymbol/s for the 30 ns value. Note that these thresholds are selected in a way to show samples of high and low threshold possibilities and point out the effect they have on the optimal base stations' locations.

6.3.1 Path Loss and Rms Delay Thresholds Equal 90 dB/60 dB and 400 ns Respectively

The first set of threshold values considered in this chapter is 90 dB for the path loss and 400 ns for the rms delay spread. Starting with the maximisation of the cost function of equation 6.5 with a trade-off factor of 0 (the rms delay spread is the only factor influencing the cost function), it is noticed that the cost function values for all the possible transmitter's locations are equal, thus any transmitter's location can be considered the optimal position. Consequently, for any transmitter's location, all the receivers' positions have their rms delay spread values less than the threshold of 400 ns and the optimisation process is totally controlled by the path loss values. The maximisation of the three objective functions with the exception of that with α equals 0 must then lead to the same optimal position obtained when the cost function of equation 6.5 is maximised with the trade-off factor α set to 1 (the objective function is defined based on path loss values only). The optimal position's coordinates obtained when the empty environment is considered are (4.175, 10.225).

Similarly, if the path loss and rms delay spread threshold values are set to 60 dB and 400 ns respectively, the optimal base station's position is controlled by the path loss values only and the maximisation of the three cost function with the exception of that with α equals 0 leads to the optimal position with coordinates (5.675, 5.725). Figure 6.1 shows the path loss distribution throughout the environment for the optimal positions (4.175, 10.225) and (5.675, 5.725). Note that the path loss at locations where a receiver cannot exist appears in dark blue. Compared to the optimal position obtained when the path loss threshold value was 90 dB, it can be seen that the base station is moved southward to a wider area with less obstacles in order to increase the free area around the base station where the signal strength is higher. In addition, more receivers' positions will be in direct line of sight with the transmitter and will receive higher signal strength. Note that for the (5.675, 5.725) position, only 38.88% of the receivers' positions will be served which means that for low path loss threshold values one base station is not enough to provide service to the whole environment.

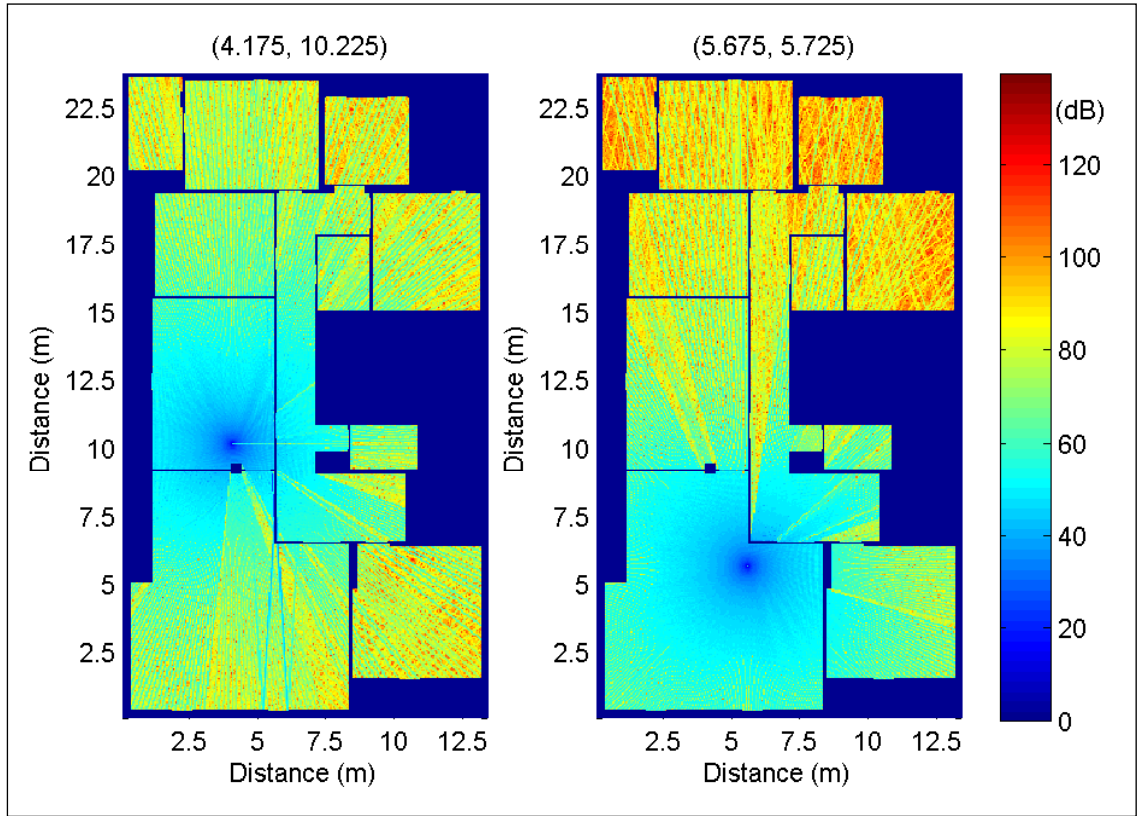


Figure 6.1: Path loss in dB at the possible receivers' positions throughout the empty environment for transmitter's position coordinates of (4.175, 10.225) and (5.675, 5.725) corresponding to 90 dB and 60 dB path loss thresholds respectively with 400 ns rms delay spread threshold

6.3.2 Path Loss and Rms Delay Thresholds Equal 90 dB and 30 ns Respectively

This section will discuss the optimisation results of the third set of threshold values: 90 dB for the path loss and 30 ns for the rms delay spread. As the rms delay spread threshold value is lowered to 30 ns, the maximisation of the cost function of equation 6.5 with the trade-off factor set to 0 (the objective function is based on the rms delay spread values only) leads to the position with coordinates (11.675, 16.225) and not to any random position as in the case of 400 ns threshold value. The optimal base station's position is then not anymore controlled by the path loss values alone but by both the path loss and the rms delay spread values. Figure 6.2 shows in cyan the receivers' positions that satisfy the path loss threshold of 90 dB and the rms delay spread of 30 ns separately.

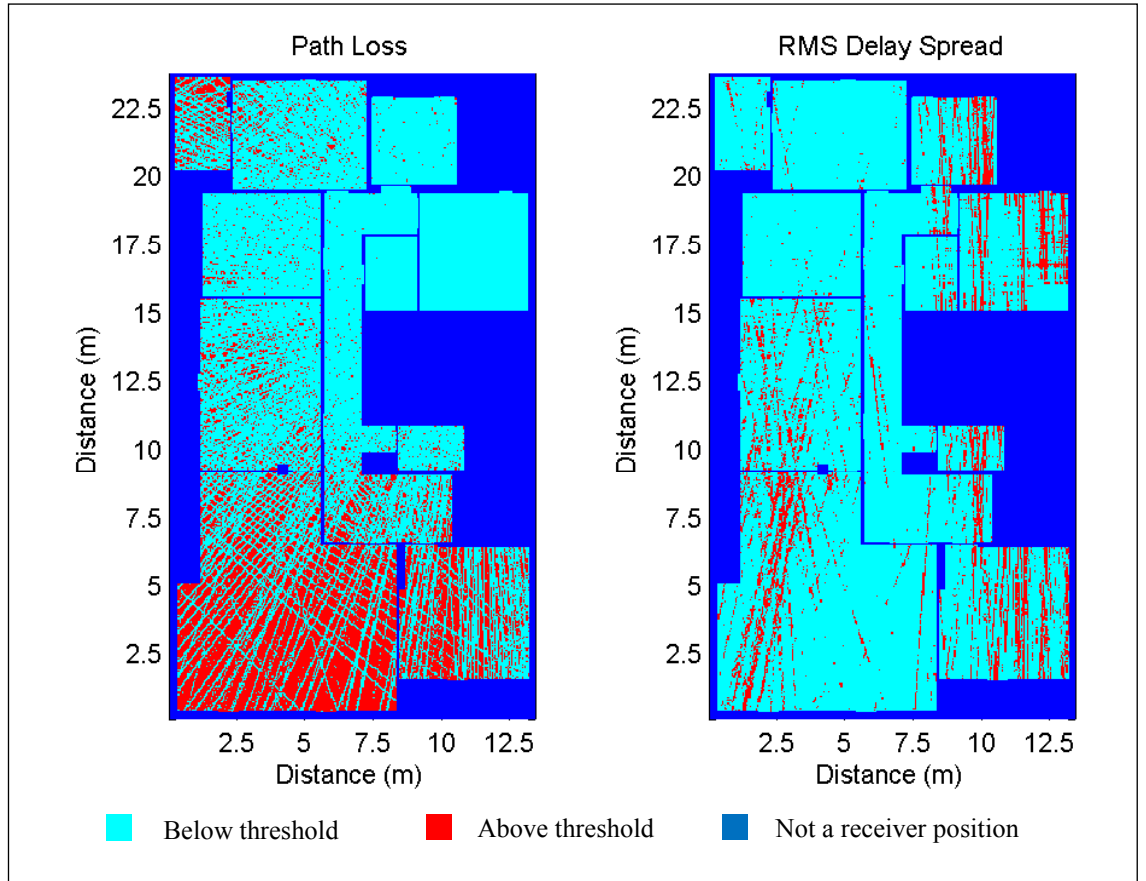


Figure 6.2: Receivers' positions having their path loss and rms delay spread below the thresholds of 90 dB and 30 ns for a transmitter's position coordinates of (11.675, 16.225)

The optimal position resulting from maximising the cost functions of equations 6.1, 6.3 and 6.5 with $\alpha=0.2$ and 0.7 is (8.675, 7.225). When α is set to 1, the optimisation of the cost function of equation 6.5 gives the same position previously obtained when the threshold values were 90 dB and 400 ns as the cost function in this case is independent of the rms delay spread values and the path loss threshold was not modified. Figure 6.3 shows the path loss over the possible receivers' positions when the base station is located at the optimal position (8.675, 7.225). Comparing the path loss distribution over the environment for the two base station's positions ((4.175, 10.225) and (8.675, 7.225)), it can be noticed that when the rms delay spread threshold is decreased, the optimal position is shifted southward in the environment and more receivers' positions have high path loss values. For the (4.175, 10.225) position, 91.31% of the receivers' positions have a path loss less than 90 dB compared to 80.14% for the position (8.675, 7.225). Although the percentage of the receivers' positions satisfying the path loss threshold criterion for the (4.175, 10.225) is higher, it is not the optimal

position as only 35.82% of the receivers' positions have their rms delay spread less than 30 ns whereas 80.14% of the receivers' positions have their rms delay spread less than 30 ns when the transmitter is at (8.675, 7.225). The higher percentage of the receivers' positions satisfying the rms delay spread condition makes the percentage of the positions satisfying both conditions (the path loss and the rms delay spread) higher and thus the optimal position changes when the rms delay spread threshold is decreased. Figure 6.4 shows the receivers' positions that satisfy the coverage conditions for the path loss and the rms delay spread each in a separate plot.

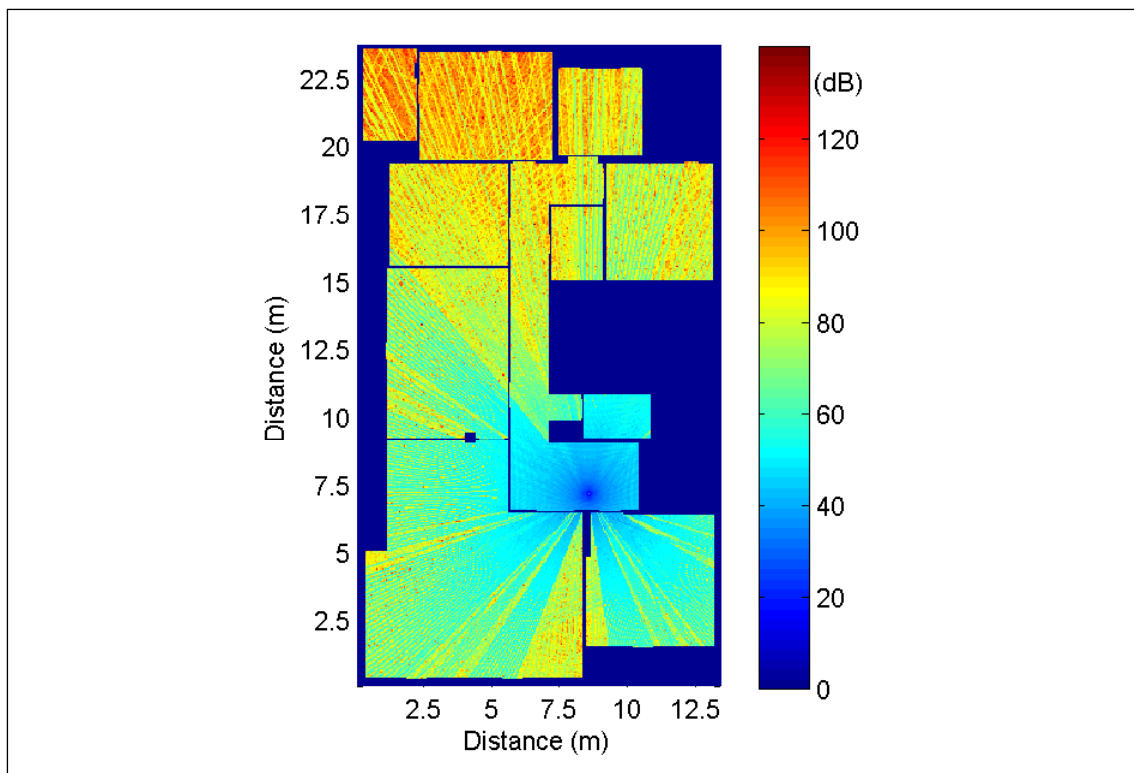


Figure 6.3: Path loss in dB at the possible receivers' positions throughout the empty environment for a transmitter's position coordinates of (8.675, 7.225)

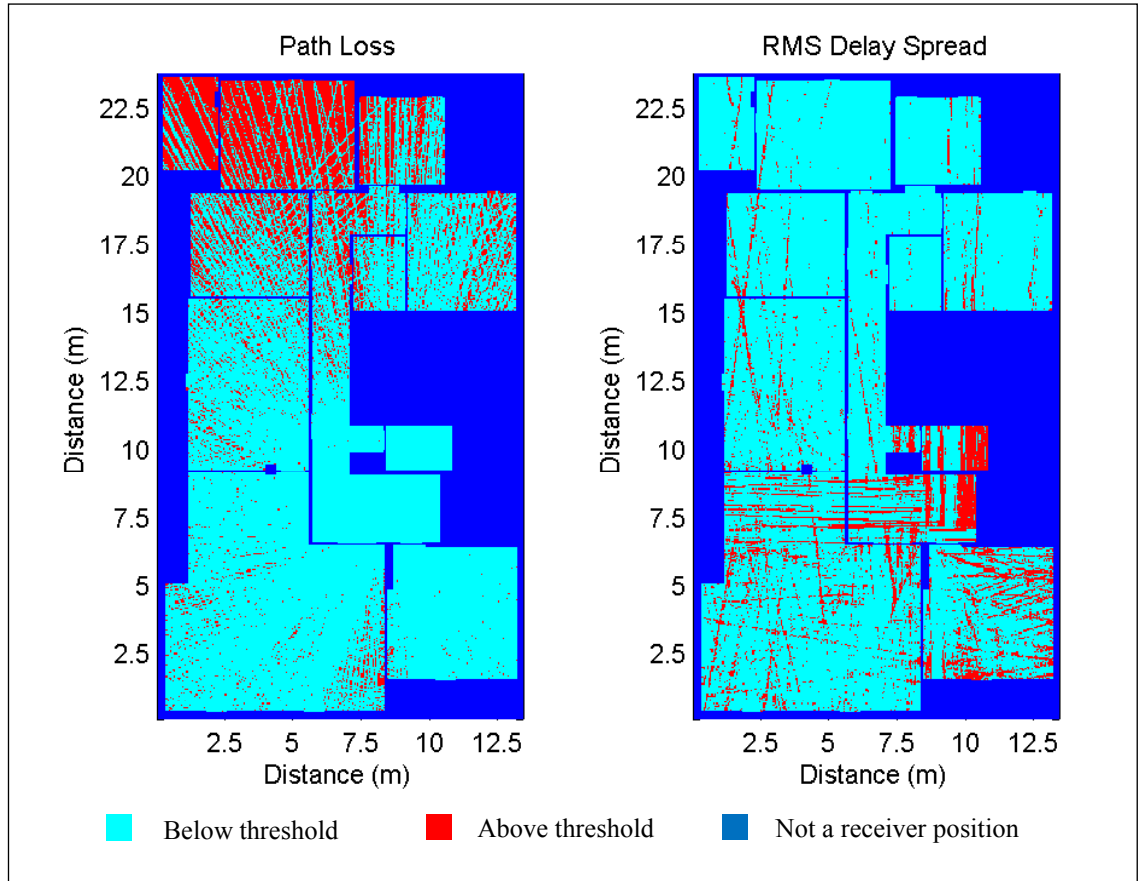


Figure 6.4: Receivers' positions having their path loss and rms delay spread below the thresholds of 90 dB and 30 ns for a transmitter's position coordinates of (8.675, 7.225)

6.3.3 Path Loss and Rms Delay Thresholds Equal 60 dB and 30 ns Respectively

The last combination of threshold values is 60 dB for the path loss and 30 ns for the rms delay spread. Maximising the objective function of equation 6.5 when α equals 0 for the 60 dB and 30 ns threshold values is equivalent to its maximisation when the thresholds are 90 dB and 30 ns as this is the case where the cost function is independent of the path loss values thus the optimal base station's position's coordinates are (11.675, 16.225). Similarly when α is set to 1, the same optimal base station's position (5.675, 5.725) is obtained when the threshold values are set to 60 dB and 400 ns or 60 dB and 30 ns as for this trade-off factor, the cost function is dependent on the path loss values only.

On the other hand, the maximisation of the cost functions of equations 6.1 and 6.5 with α set to 0.2 and 0.7 results in the position (8.675, 7.225) whereas for the same path loss threshold but with higher rms delay spread threshold (400 ns), the optimal position's coordinates were (5.675, 5.725). Figure 6.5 shows the state of each receiver's

position whether it has a path loss lower than the threshold value or not for the latter two base station's positions. It can be noticed from Figure 6.5 that if the base station is located at (5.675, 5.725), more receivers' positions have their path loss less than 60 dB (38.88% as opposed to 30.26% for the position (8.675, 7.225)). Despite this, the optimal position is not (5.675, 5.725). This must be due to the rms delay spread values. Looking into the receivers' positions that satisfy the rms delay threshold criterion for the two positions (Figure 6.6), it can be seen that for the position (5.675, 5.725), in the area where the path loss is lower than its threshold value, most receivers' positions have their rms delay spread higher than 30 ns. A receiver's position satisfying the rms delay conditions with a low threshold value can be due to the fact that a single ray is reaching that position and hence the rms delay spread is zero or the rays are bouncing back quickly to the receiver's position due to nearby reflections. As the transmitter's position with coordinates (5.675, 5.725) is in a wide area without too many close walls or doors, the rms delay spread values for most positions with low path loss is higher than the threshold. The percentage of receivers' positions with rms delay spread less than 30 ns is 47.02% for the base station's position (5.675, 5.725) and 87.8% for the position (8.675, 7.225). The higher percentage of receivers' positions meeting the rms delay spread coverage condition for the position (8.675, 7.225) increases the probability of getting more receivers' positions that satisfy the path loss and the rms delay spread criteria. For the (5.675, 5.725), 10.85% of the receivers' positions have guaranteed coverage as opposed to 23.2% for the optimal transmitter's position (8.675, 7.225).

The optimisation of the cost function of equation 6.3 gives the same transmitter's coordinates as the one of equation 6.1 for the three previous threshold values combinations whereas for the thresholds of 60 dB and 30 ns, different optimal position is obtained: (8.675, 4.225). It is previously mentioned that for the position (8.675, 7.225) 30.26% of the receivers' positions have a path loss less than 60 dB and 23.2% have both, the path loss and rms delay spread less than the threshold values. As for the (8.675, 4.225) position, 33.74% of the receivers' positions have the path loss less than the threshold whereas 20.6% satisfy both threshold criteria. Therefore, for the (8.675, 7.225), 7.06% of the receivers' positions satisfies the path loss threshold criterion alone as opposed to 13.14% for the (8.675, 4.225) which makes the value of the objective function of equation 6.3 higher for the (8.675, 4.225) position and it becomes the optimal position.

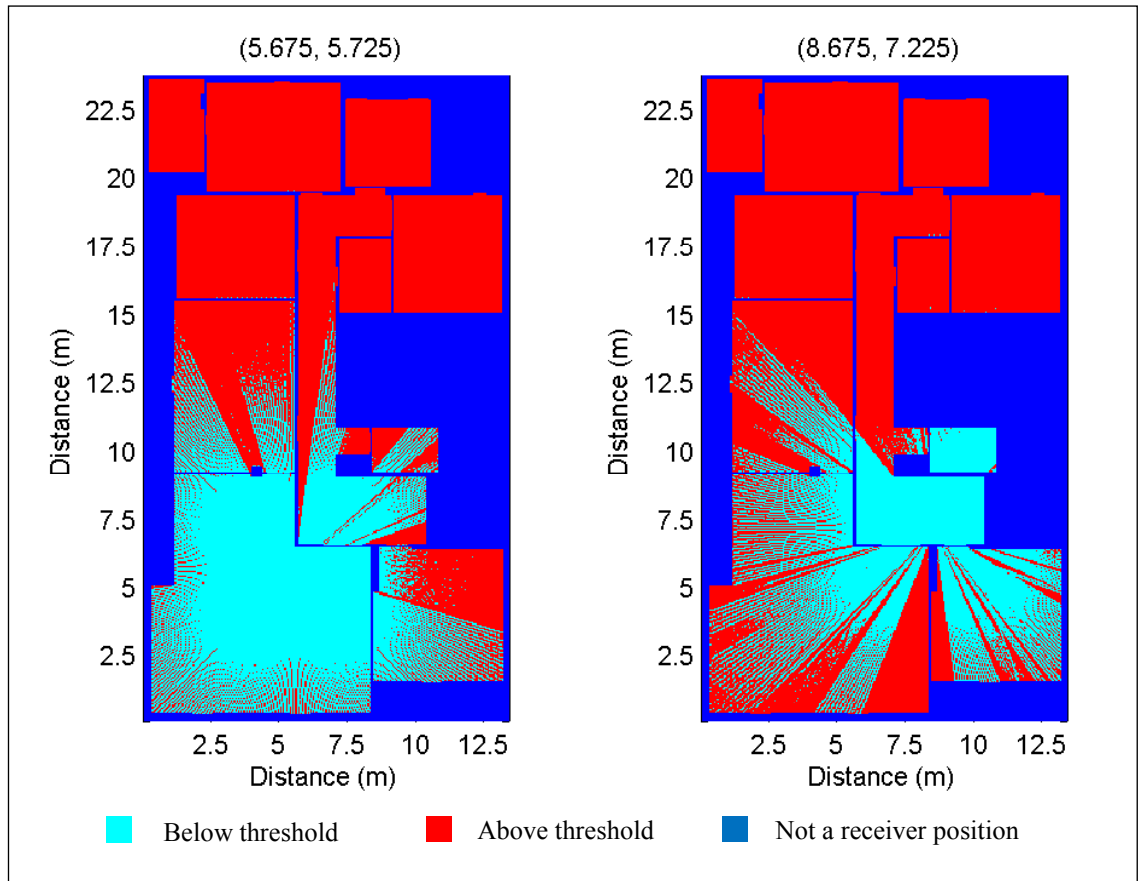


Figure 6.5: Receivers' positions having their path loss below the thresholds of 60 dB for a transmitter's position coordinates of (5.675, 5.725) and (8.675, 7.225)

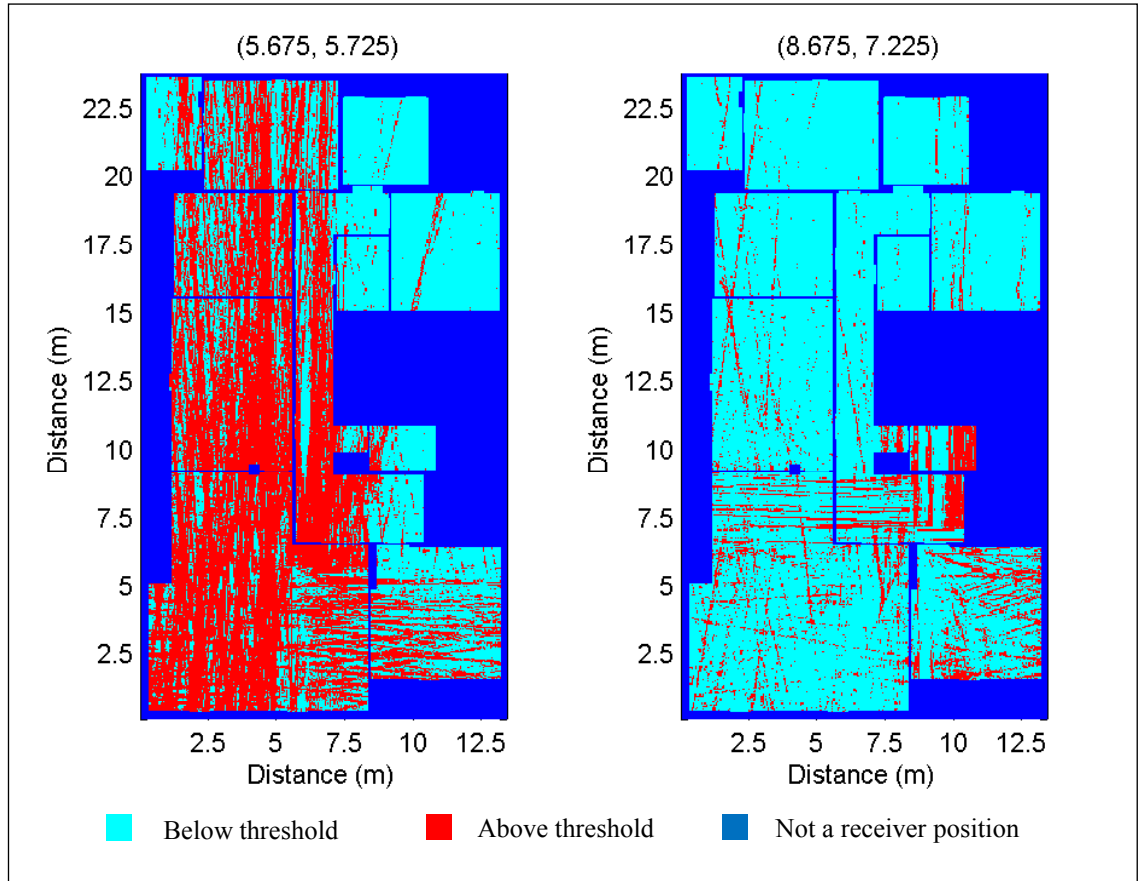


Figure 6.6: Receivers' positions having their rms delay spread below the thresholds of 30 ns for a transmitter's position coordinates of (5.675, 5.725) and (8.675, 7.225)

Table 6.1 summarises the base station's positions' Cartesian coordinates that maximise the three cost functions defined in this chapter for different parameters when the environment is served by a single base station.

Examining the coverage that different optimal base station's positions provides for different threshold values, it is noticed that as the threshold values are decreased, the coverage percentage significantly deteriorates and may reach a value less than quarter of the environment and hence a single base station will not be enough to serve the environment and multiple transmitters must be used. In the following two sections, two and three transmitters' scenarios will be discussed.

	Cost Function of equation 6.1	Cost Function of equation 6.3	Cost Function of equation 6.5	
PL _{th} =90 dB DL _{th} =400 ns	(4.175, 10.225)	(4.175, 10.225)	$\alpha=0$	Any position
			$\alpha=0.2$	(4.175, 10.225)
			$\alpha=0.7$	(4.175, 10.225)
			$\alpha=1$	(4.175, 10.225)
PL _{th} =90 dB DL _{th} =30 ns	(8.675, 7.225)	(8.675, 7.225)	$\alpha=0$	(11.675, 16.225)
			$\alpha=0.2$	(8.675, 7.225)
			$\alpha=0.7$	(8.675, 7.225)
			$\alpha=1$	(4.175, 10.225)
PL _{th} =60 dB DL _{th} =400 ns	(5.675, 5.725)	(5.675, 5.725)	$\alpha=0$	Any position
			$\alpha=0.2$	(5.675, 5.725)
			$\alpha=0.7$	(5.675, 5.725)
			$\alpha=1$	(5.675, 5.725)
PL _{th} =60 dB DL _{th} =30 ns	(8.675, 7.225)	(8.675, 4.225)	$\alpha=0$	(11.675, 16.225)
			$\alpha=0.2$	(8.675, 7.225)
			$\alpha=0.7$	(8.675, 7.225)
			$\alpha=1$	(5.675, 5.725)

Table 6.1: Optimal base station's positions in the empty environment using the three predefined cost functions for different parameters' values

6.4 Two Transmitters' Locations Optimisation Results for The Empty Environment

Based on the results of the single transmitter's scenario, it was shown that as the threshold values above which a receiver loses the service decrease, a single transmitter will not be enough to serve a wide area of the environment and hence more than one base station must be positioned in the environment. In this section, two base stations are assumed to serve the environment. The optimal positions obtained after maximising the three cost functions for the same path loss and rms delay threshold values used in the single transmitter's scenario will be discussed in addition to the effect of using two transmitters on the coverage area.

6.4.1 Path Loss and Rms Delay Thresholds Equal 90 dB/60 dB and 400 ns Respectively

In this section, the rms delay spread threshold is set to 400 ns. This is the case where the three cost functions become equivalent and independent of the rms delay spread values as all receivers' positions have their rms delay spread less than the threshold. The only exception is the case of α equals 0 where any two transmitters' locations can be considered optimal. As for the path loss threshold, it is set to either 90 dB or 60 dB. When it is equal to 90 dB, the optimal base stations' coordinates are (7.175, 4.225) for the first base station and (5.675, 19.225) for the second one. The coverage percentage in this case is 99.72% while it was 91.31% in the single transmitter case. The coverage percentage was already high when a single transmitter was used. However, the addition of the second base station lowers the path loss values throughout the environment. On the other hand, when the path loss threshold is decreased to 60 dB, the optimal coordinates of the two base stations are (5.675, 4.225) and (5.675, 17.725) and the coverage percentage has almost doubled when two base stations are used instead of one and it has reached 73.63%. Figure 6.7 shows the path loss throughout the environment for the optimal base stations' positions obtained for the 90 dB and 60 dB thresholds. In the 90 dB scenario, the environment looks to be split halfway horizontally in the plan view where each part is served by a transmitter that is somehow located in the centre of the area it is serving. Note that when the path loss threshold is decreased, the base station serving the southern part of the environment moved away from the wall so that the area with low path loss is increased.

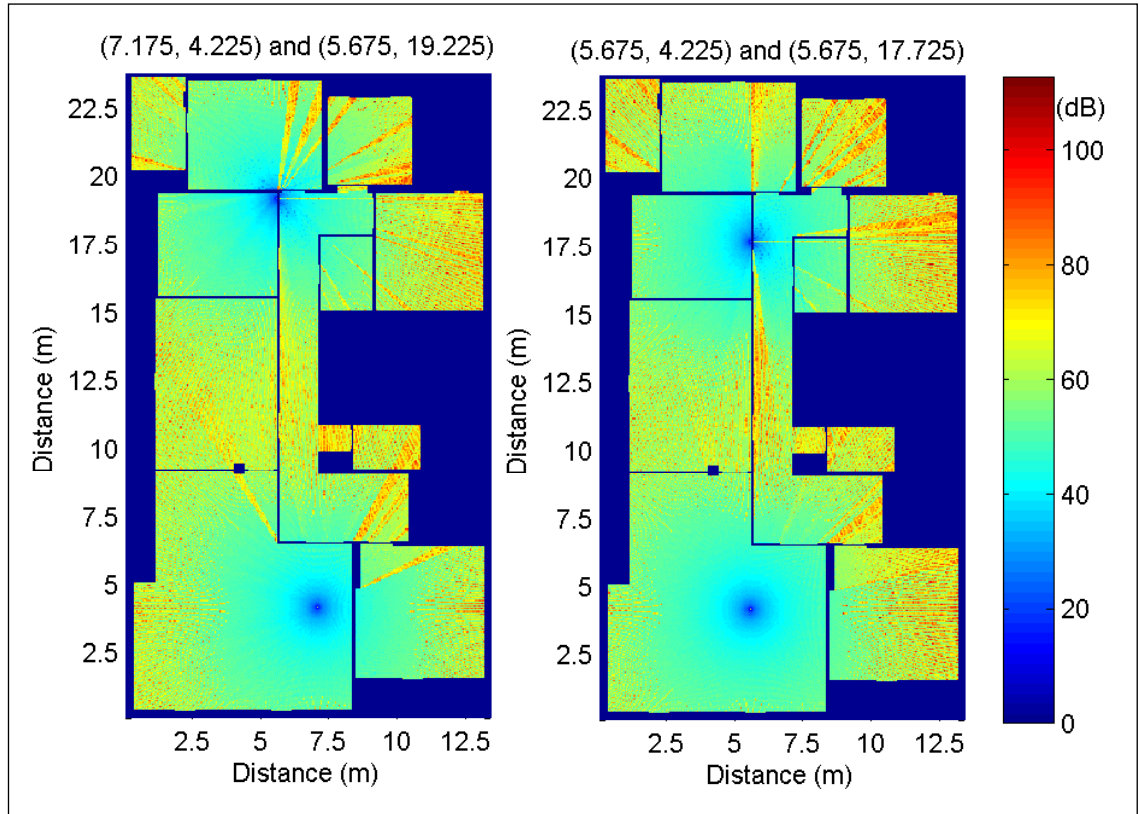


Figure 6.7: Path loss in dB at the possible receivers' positions throughout the empty environment served by two transmitters located at their optimal locations for path loss thresholds of 90 dB or 60 dB with rms delay spread threshold set to 400 ns

6.4.2 Path Loss and Rms Delay Thresholds Equal 90 dB and 30 ns Respectively

The third set of threshold values to be considered consists of 90 dB for the path and 30 ns for the rms delay spread. The number of receivers' positions having their rms delay spread lower than 30 ns vary from one transmitter's position to another, therefore, no longer any combination of two transmitters' positions maximises the cost function of equation 6.5 with the trade-off parameter α set to 0. The coordinates of the optimal base stations' positions are: (11.675, 16.225) and (11.675, 17.725). The corresponding path loss values throughout the environment are shown in Figure 6.8. The first base station's position is the same obtained when the environment was assumed to be served by a single base station whereas the second base station is adjacent to the first one. The second base station looks redundant in this case, but before confirming this assumption, the coverage percentage must be calculated and compared to that of the single transmitter's scenario. When the base station located at (11.675, 16.225) is considered to be serving the environment alone, 88.67% of the receivers' positions have their rms

delay spread lower than 30 ns, 72.53% of them have their path loss less than 90 dB and 63.64% of them have both their path loss and rms delay spread less than 90 dB and 30 ns respectively. When an additional base station is positioned at (11.675, 17.725), the percentage of the receivers' positions having their rms delay spread below 30 ns is lowered to 86.58%. As previously explained, when multiple base stations are placed in the environment, each receiver is served by the base station providing the higher field strength or equivalently the lower path loss regardless of the corresponding rms delay spread value. The receivers' positions can be then split into two sets, each served by one of the base stations. In order to check how the receivers' positions are allocated among the base stations, a plot of the rms delay spread state throughout the environment is produced for each base station separately (Figure 6.9). In each plot, the yellow colour represents the receivers' positions served by the other base station whereas the cyan means that the receiver's position has its rms delay value lower than 30 ns and the red colour means that the receiver's position has its rms delay value higher than 30 ns. It can be seen that the biggest continuous area served by the same base station is around the base station and for the rest of the environment the areas served by each base station are interleaved. Out of the 86.58% of the receivers' positions with rms delay spread less than the threshold, 43.47% are served by the base station at (11.675, 16.225) and 43.11% are served by the one located at (11.675, 17.725). On the other hand, the additional base station has increased the percentage of receivers' positions with path loss less than 90 dB by 13.7%. It has also increased the percentage of receivers' positions with path loss less than 90 dB and rms delay spread less than 30 ns to reach 74.1%. Therefore adding the second base station next to the first one has guaranteed the service for an extra 10.46% of receivers' positions and it is not totally redundant though it has provided a limited coverage improvement.

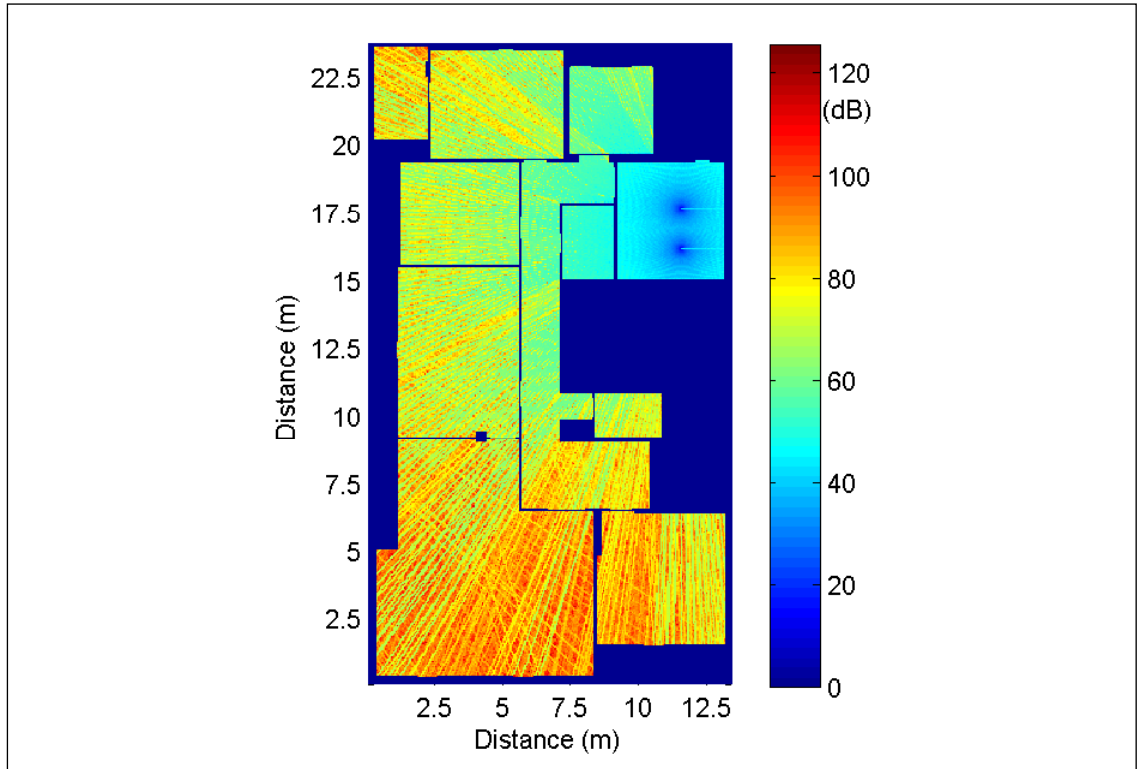


Figure 6.8: Path loss in dB at the possible receivers' positions throughout the empty environment for two transmitters with coordinates of (11.675, 16.225) and (11.675, 17.725)

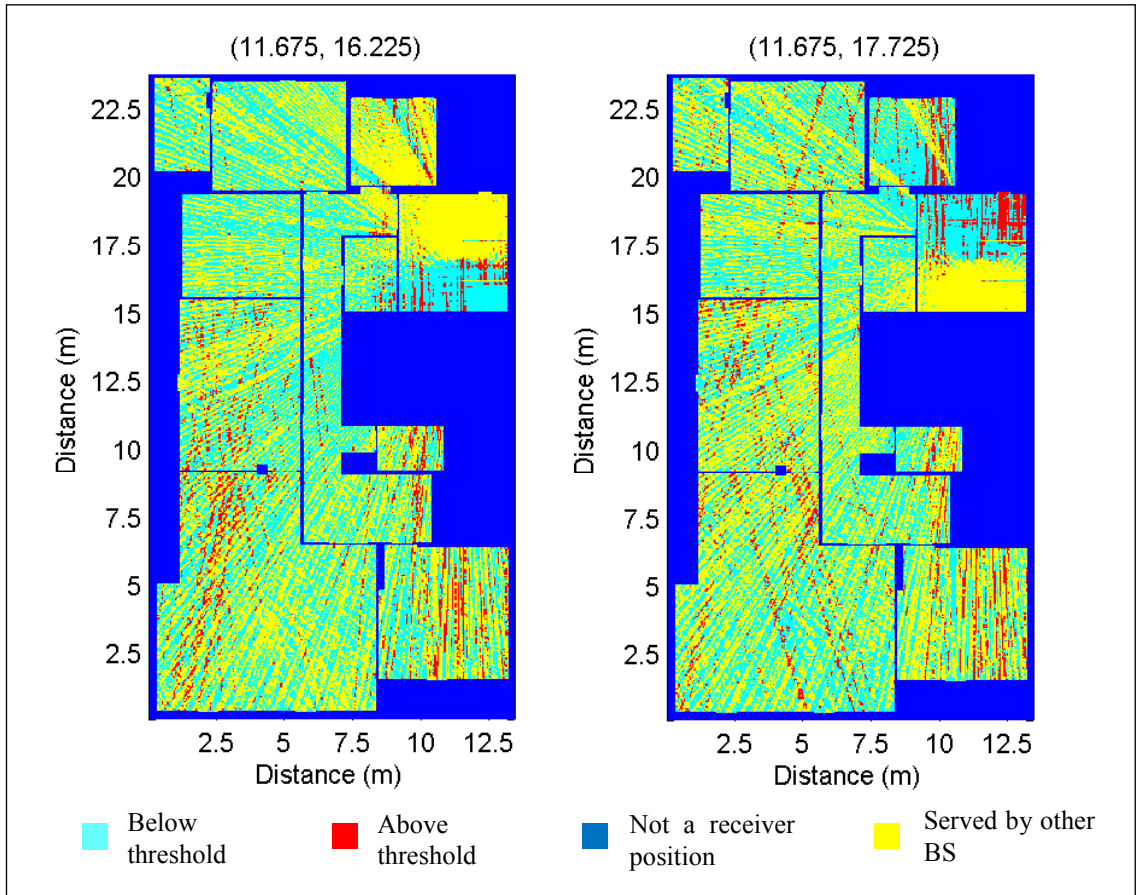


Figure 6.9: Receivers' positions having their rms delay spread below the thresholds of 30 ns for transmitters' position coordinates (11.675, 16.225) and (11.675, 17.725) separately

Moreover, the maximisation of equation 6.5 with α set to 1 and with thresholds of 90 dB and 30 ns produces the same positions obtained with the thresholds being 90 dB and 400 ns as the objective function does not depend on rms delay spread values in this case.

For the remaining cases, or in other words the maximisation of equations 6.1, 6.3 and 6.5 with α equal to 0.2 and 0.7 yield the same optimal positions with coordinates (8.675, 7.225) and (11.675, 16.225). Again one of the base stations is located at the same place of the single transmitter's case whereas the second one is not close to it. Figure 6.10 shows the corresponding path loss distribution over the environment where it can be noticed that the addition of the second base station has decreased the maximum path loss values over the environment as each receiver is allocated to the base station that provides the highest field strength (lowest path loss). The improvement that the second base station added to the environment is an increase in the receivers' positions with path loss lower than the threshold from 80.14% to 97.13% and an increase in the receivers' positions with both the path loss and rms delay spread below the thresholds from 68.79% to 82.59%. Note that unlike the case where the two base stations were next to each other, the allocation of the receivers' into the two base stations are somehow in two big blocks with some interleaved areas. This is shown in Figure 6.11 where the magenta represents the receivers' positions served by the base station positioned at (8.675, 7.225) and the green represents the ones served by the base station located at (11.675, 16.225) although some of the positions that are supposed to be served by either base stations may not enjoy service as this is dependent on their path loss and rms delay spread values compared to the selected thresholds.

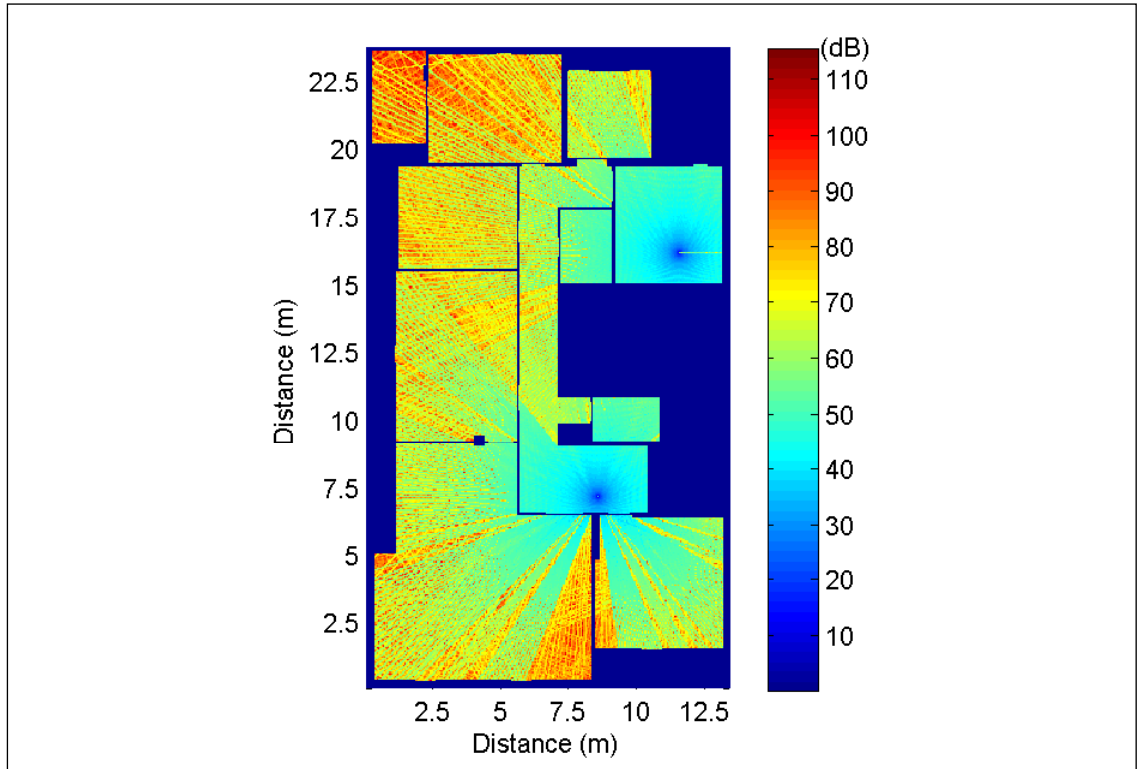


Figure 6.10: Path loss in dB at the possible receivers' positions throughout the empty environment for two transmitters with coordinates of (8.675, 7.225) and (11.675, 16.225)

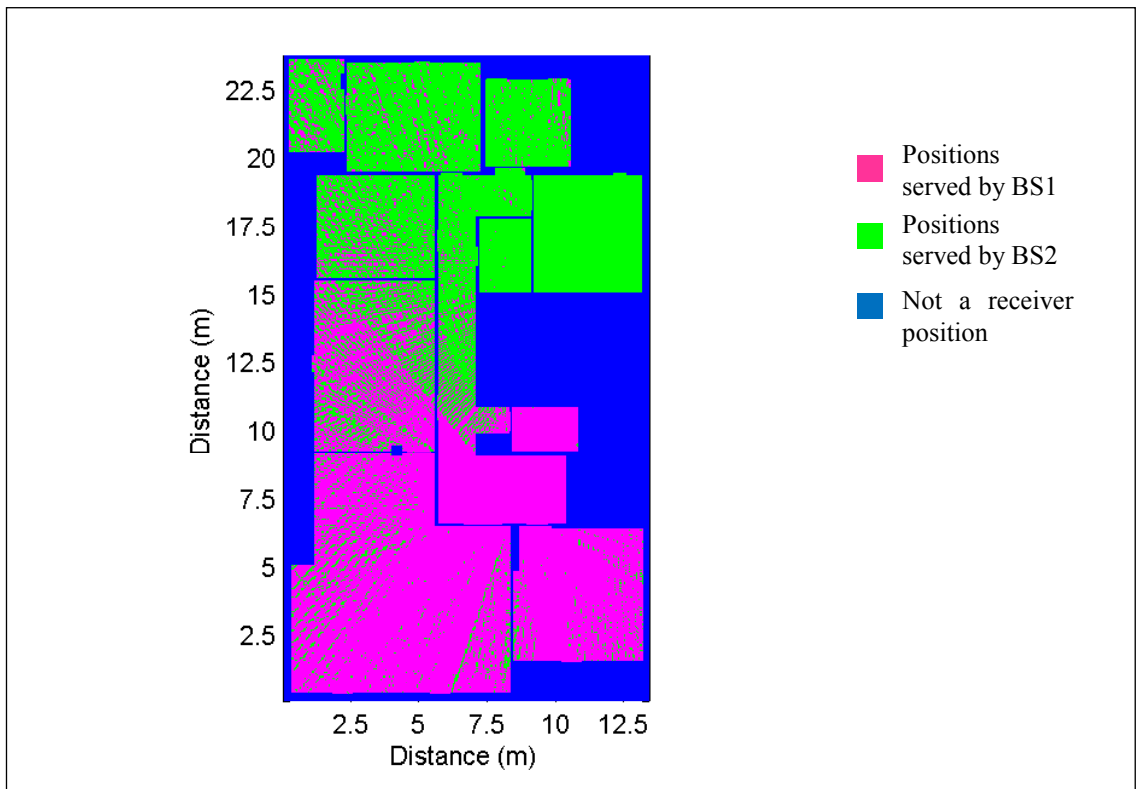


Figure 6.11: Receivers' allocation into the base stations BS1 and BS2 with coordinates (8.675, 7.225) and (11.675, 16.225) respectively

6.4.3 Path Loss and Rms Delay Thresholds Equal 60 dB and 30 ns Respectively

The last set of threshold values considered for the two transmitters' scenario is with both the rms delay spread and path loss being low (60 dB and 30 ns). As both threshold values are low, even for the optimal base stations' positions, the coverage percentage is expected to be low. In addition, the optimal positions obtained for the various cost functions are different as it can be seen in Table 6.2 that summarises the optimal base stations' positions obtained after maximising the three cost functions with the four sets of threshold values.

Starting with the cost function of equation 6.1, the coordinates of the first base station are equal to that obtained when a single transmitter is assumed to serve the environment thus the coordinates of the two base stations are (8.675, 7.225) and (8.675, 19.225). Looking into the path loss distribution over the environment (Figure 6.12), the areas with the path loss less than 60 dB are limited. 42.94% of the receivers' positions satisfy both coverage criteria and have guaranteed service as opposed to 23.2% when a single base station is used. In addition, 58.05% of the receivers' positions satisfy at least the path loss criteria therefore, 15.56% of them may have some limited service. Note that compared to the scenario when the same path loss threshold is used but with a higher rms delay spread threshold (400 ns), the two base stations have moved away from central positions toward corners.

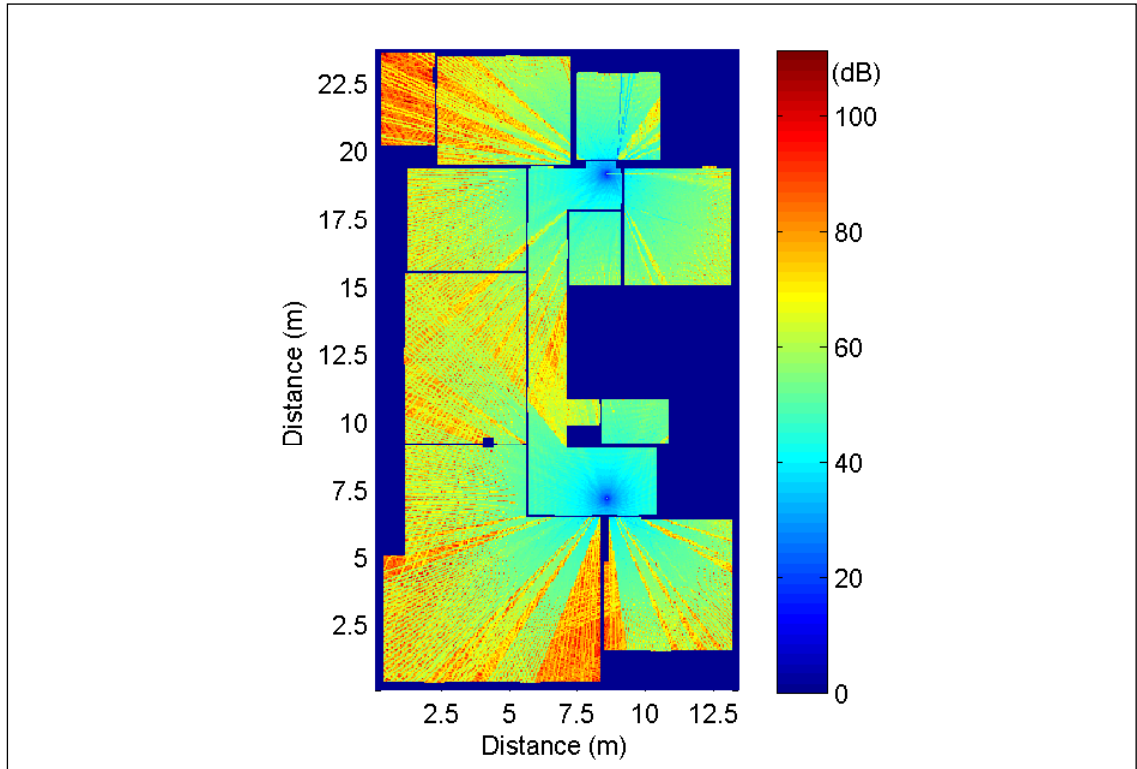


Figure 6.12: Path loss in dB at the possible receivers' positions throughout the empty environment for two transmitters with coordinates of (8.675, 7.225) and (8.675, 19.225)

On the other hand, the maximisation of equation 6.3 results in (8.675, 4.225) and (5.675, 17.725) as optimal coordinates. In this case, one of the base stations is also located at the same place as the one transmitter scenario. This cost function is more influenced by the path loss as its value must be below the threshold whereas the rms delay spread may or may not be below the threshold. Consequently, one of the base stations is somehow in a central location which increases the number of receivers' positions receiving a less attenuated signal with path loss less than 60 dB (Figure 6.13). As for the coverage area, 34.23% of the receivers' positions have guaranteed coverage in addition to 35.8% having a risky service depending on how much higher the corresponding rms delay spread is compared to the threshold value. The improvement over the single transmitter scenario is by 13.63% for the positions with assured service and 22.66% with uncertain service. In other words, a total of 70.03% for the two transmitters' case and 33.74% for the single transmitter case of the receivers' positions have their path loss less than 60 dB regardless of the rms delay spread value and have either a guaranteed or risky service.

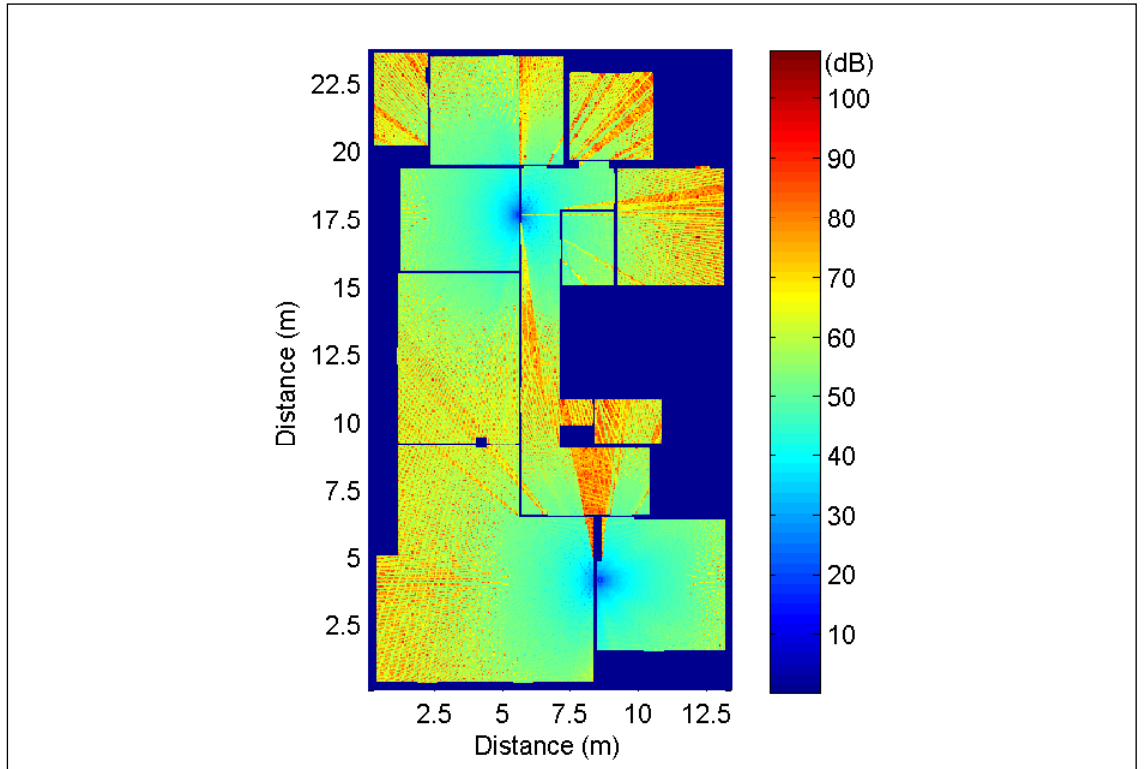


Figure 6.13: Path loss in dB at the possible receivers' positions throughout the empty environment for two transmitters with coordinates of (8.675, 4.225) and (5.675, 17.725)

The remaining objective function is that of equation 6.5. Maximising this equation with the trade-off factor set to 0 and thresholds of 60 dB and 30 ns is equivalent to maximising it with thresholds of 90 dB and 30 ns. Similarly, maximising it with trade-off factor set to 1 makes it a function of path loss values only and the optimal positions are that obtained with thresholds of 60 dB and 400 ns. When the trade-off is set to 0.2, the number of receivers' positions with rms delay spread less than 30 ns have higher influence on the cost function values than those with path loss less than 60 dB. The optimal base stations' coordinates obtained are (8.675, 7.225) and (11.675, 16.225) with the latter being one of those obtained when the same function was totally controlled by the rms delay spread values ($\alpha=0$). The area with guaranteed coverage is of 37.73% in addition to 9.64% with risky service. Alternatively, when the trade-off factor α is set to 0.7 higher priority is given to the path loss values distribution with the rms delay values still having influence, thus the optimal positions obtained are equal to that obtained after the optimisation of equation 6.3.

	Cost Function of equation 6.1	Cost Function of equation 6.3	Cost Function of equation 6.5	
PL_{th}=90 dB DL_{th}=400 ns	(7.175, 4.225) (5.675, 19.225)	(7.175, 4.225) (5.675, 19.225)	$\alpha=0$	Any 2 positions
			$\alpha=0.2$	(7.175, 4.225) (5.675, 19.225)
			$\alpha=0.7$	(7.175, 4.225) (5.675, 19.225)
			$\alpha=1$	(7.175, 4.225) (5.675, 19.225)
PL_{th}=90 dB DL_{th}=30 ns	(8.675, 7.225) (11.675, 16.225)	(8.675, 7.225) (11.675, 16.225)	$\alpha=0$	(11.675, 16.225) (11.675, 17.725)
			$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225)
			$\alpha=0.7$	(8.675, 7.225) (11.675, 16.225)
			$\alpha=1$	(7.175, 4.225) (5.675, 19.225)
PL_{th}=60 dB DL_{th}=400 ns	(5.675, 4.225) (5.675, 17.725)	(5.675, 4.225) (5.675, 17.725)	$\alpha=0$	Any 2 positions
			$\alpha=0.2$	(5.675, 4.225) (5.675, 17.725)
			$\alpha=0.7$	(5.675, 4.225) (5.675, 17.725)
			$\alpha=1$	(5.675, 4.225) (5.675, 17.725)
PL_{th}=60 dB DL_{th}=30 ns	(8.675, 7.225) (8.675, 19.225)	(8.675, 4.225) (5.675, 17.725)	$\alpha=0$	(11.675, 16.225) (11.675, 17.725)
			$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225)
			$\alpha=0.7$	(8.675, 4.225) (5.675, 17.725)
			$\alpha=1$	(5.675, 4.225) (5.675, 17.725)

Table 6.2: Optimal base stations' positions in the empty environment using the three predefined cost functions for different parameters' values (2 base stations)

6.5 Three Transmitters' Locations Optimisation Results for The Empty Environment

Depending on the threshold values of both the rms delay spread and the path loss the coverage area varies. As one of the thresholds or both get lower, the coverage percentage decreases and the use of a single base station is not enough. Adding a second base station has improved the coverage for some cases but not all of them, thus a third base station is added and the optimisation of the three cost functions for different parameters is done where the results are summarised in Table 6.3.

6.5.1 Path Loss and Rms Delay Thresholds Equal 90 dB/60 dB and 400 ns Respectively

It was previously discussed that when the rms delay spread threshold is set to 400 ns, the cost functions become equivalent and produce the same optimal base stations coordinates with the exception of that of equation 6.5 with α equals 0 that gives any combination of random transmitters' positions. Two sets of parameters presented in this chapter have the rms delay spread threshold equals 400 ns, one with 90 dB and the other with 60 dB path loss thresholds.

When the path loss threshold is set to 90 dB, the use of two transmitters' positions at the optimal coordinates provides 99.72% coverage. The two base stations are then covering almost all the environment and the addition of a third base station will be redundant. It will only decrease the path loss for some of the receivers' positions. The optimal coordinates of the three base stations are (7.175, 4.225), (5.675, 16.225) and (5.675, 19.225). The new coverage is now 99.98%.

On the other hand, when the path loss threshold is changed to 60 dB, two base stations provided service to 73.63% of the possible receivers' positions. After adding a third base station, the optimal coordinates are at (5.675, 4.225), (7.175, 13.225) and (5.675, 20.725) and they provide coverage to 84.53% of the possible receivers locations. Examining Figure 6.14 that shows the path loss when the base stations are at their optimal positions, it can be noticed that the environment is split horizontally in the plan view into three parts and each transmitter is centred inside the area it is mainly serving. The receivers' allocation is shown in Figure 6.15 where the magenta, the green and the red represent the areas served by the base stations with coordinates (5.675, 4.225), (7.175, 13.225) and (5.675, 20.725) respectively. Note that the allocation is not equal among the base stations where the first base station covers 41.05% of the possible receivers' positions, the second and the third cover 30.52% and 28.43% respectively.

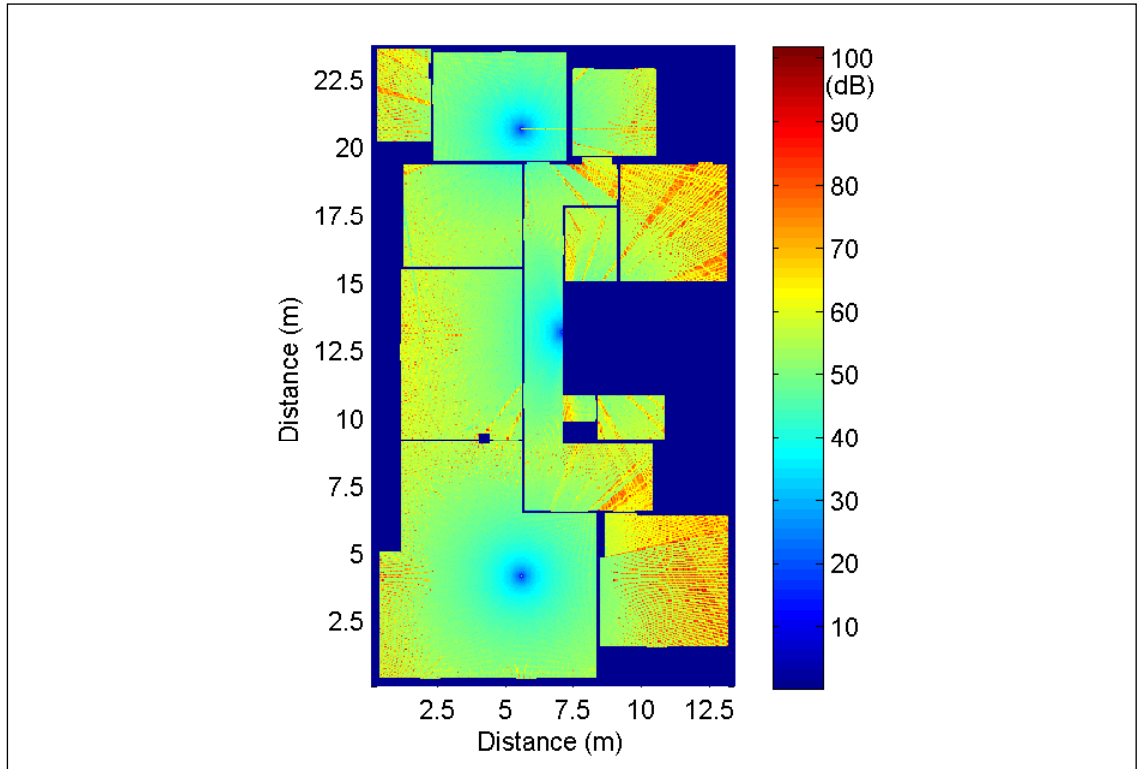


Figure 6.14: Path loss in dB at the possible receivers' positions throughout the empty environment for three transmitters with coordinates of (5.675, 4.225), (7.175, 13.225) and (5.675, 20.725)

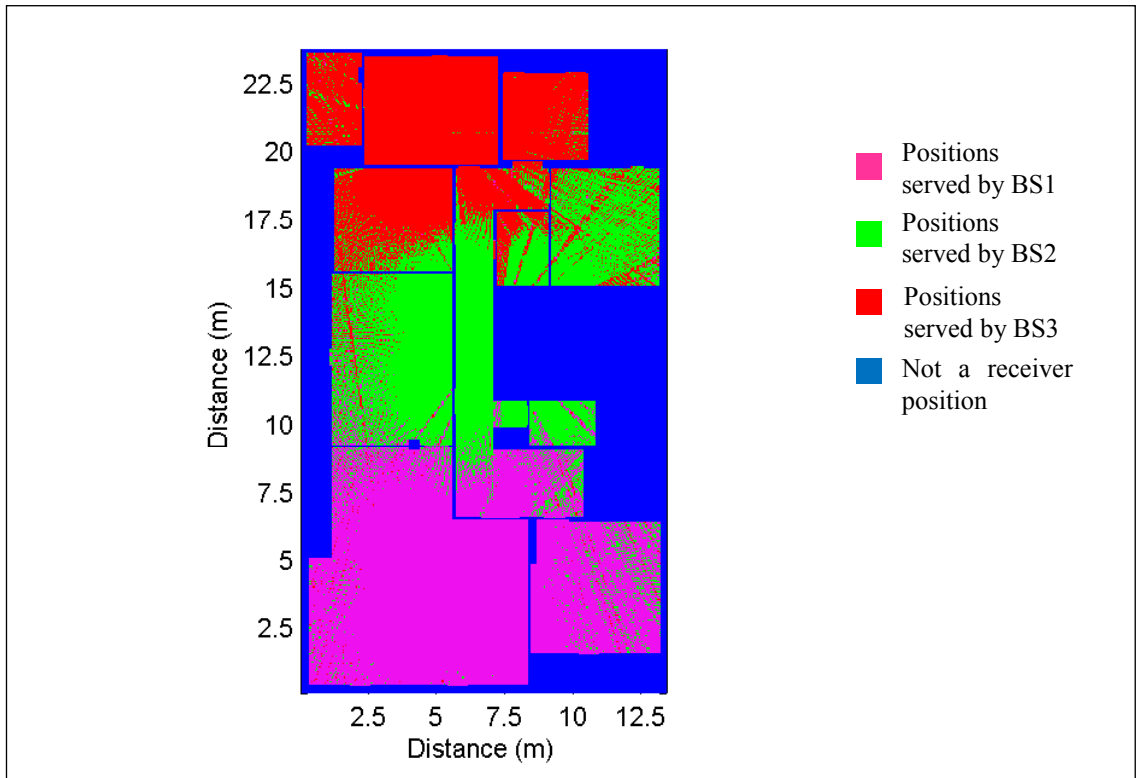


Figure 6.15: Receivers' allocation into the base stations BS1, BS2 and BS3 with coordinates (5.675, 4.225), (7.175, 13.225) and (5.675, 20.725) respectively

	Cost Function of equation 6.1	Cost Function of equation 6.3	Cost Function of equation 6.5	
PL_{th}=90 dB DL_{th}=400 ns	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	$\alpha=0$	Any 3 positions
			$\alpha=0.2$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)
			$\alpha=0.7$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)
			$\alpha=1$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)
PL_{th}=90 dB DL_{th}=30 ns	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	$\alpha=0$	(11.675, 16.225) (11.675, 17.725) (13.175, 17.725)
			$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)
			$\alpha=0.7$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)
			$\alpha=1$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)
PL_{th}=60 dB DL_{th}=400 ns	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	$\alpha=0$	Any 3 positions
			$\alpha=0.2$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)
			$\alpha=0.7$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)
			$\alpha=1$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)
PL_{th}=60 dB DL_{th}=30 ns	(8.675, 7.225) (2.675, 16.225) (8.675, 20.725)	(8.675, 4.225) (2.675, 16.225) (8.675, 20.725)	$\alpha=0$	(11.675, 16.225) (11.675, 17.725) (13.175, 17.725)
			$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)
			$\alpha=0.7$	(8.675, 4.225) (2.675, 16.225) (8.675, 20.725)
			$\alpha=1$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)

Table 6.3: Optimal base stations' positions in the empty environment using the three predefined cost functions for different parameters' values (3 base stations)

6.5.2 Path Loss and Rms Delay Thresholds Equal 90 dB and 30 ns Respectively

The maximisation of equations 6.1, 6.3 and 6.5 for α equals 0.2 and 0.7 when the thresholds are set to 90 dB and 30 ns leads to the same optimal positions with coordinates (8.675, 7.225), (11.675, 16.225) and (11.675, 17.725). Two of the base stations are placed exactly as these obtained in the two transmitters' case and the third is just next to that located at (11.675, 16.225). In terms of coverage area, the third base station has just increased the receivers' locations with guaranteed service by 0.71% to reach 83.3% and these with limited service by 1.81% which means the third base station does not add much to the system and can be ignored in this case. It has not even decreased the path loss for significant areas as can be seen in Figure 6.16 compared to Figure 6.10.

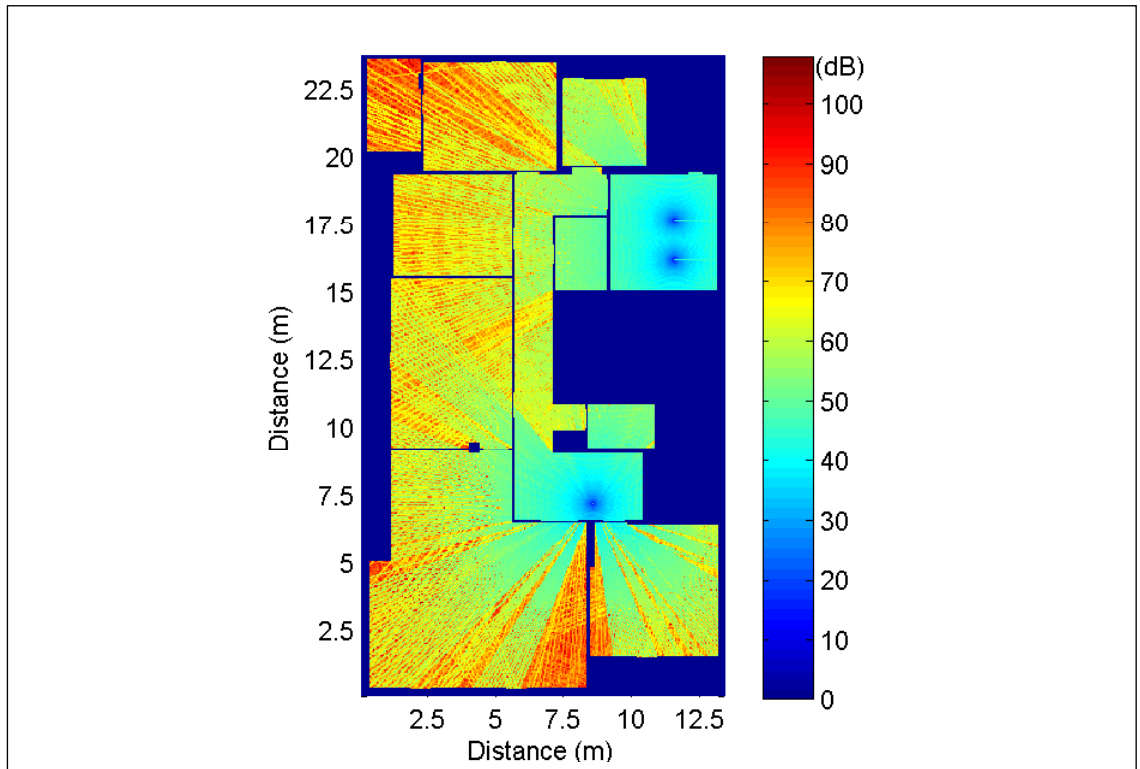


Figure 6.16: Path loss in dB at the possible receivers' positions throughout the empty environment for three transmitters with coordinates of (8.675, 7.225), (11.675, 16.225) and (11.675, 17.725)

On the other hand, the maximisation of equation 6.5 as a function of the time parameter only ($\alpha=0$) generates three locations that are next to each other; the same positions obtained with the two transmitters' case at (11.675, 16.225) and (11.675,

17.725) in addition to the third one just adjacent to them at (13.175, 17.725). As the three base stations are very close to each other the receivers' allocation is supposed to be dispersed. This is shown in Figure 6.17. Note that 37.44% of the possible receivers' positions are allocated to BS1, 37.29% and 25.27% to BS2 and BS3 respectively although under the specified threshold values some of the receivers' locations will not have service. More specifically, 77.97% of the possible receivers' locations have assured service and 13.81% have uncertain service and that is with an increase of just 3.87% and 5.55% respectively compared to the two transmitters' model.

Furthermore, the maximisation of equation 6.5 as a function of path loss only ($\alpha=1$) is equivalent to that discussed in section 6.5.1 when the path loss threshold is equal to 90 dB.

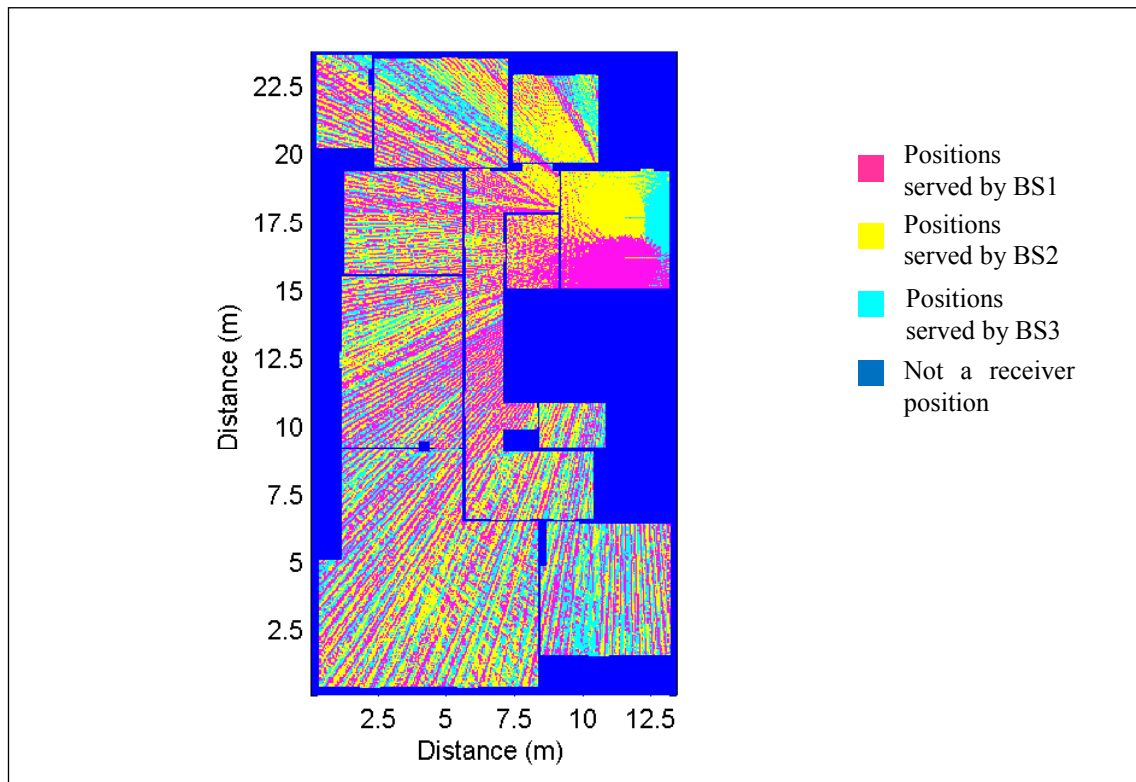


Figure 6.17: Receivers' allocation into the base stations BS1, BS2 and BS3 with coordinates (11.675, 16.225), (11.675, 17.725) and (13.175, 17.725) respectively

6.5.3 Path Loss and Rms Delay Thresholds Equal 60 dB and 30 ns Respectively

Based on the two transmitters' coverage results for the low thresholds of 60 dB and 30 ns, a third based station is necessary to increase the area enjoying the wireless service. Starting with the result of the optimisation of equation 6.1 and compared to these obtained for the same path loss threshold but with the rms delay spread threshold set to 400 ns, the optimal base stations were moved toward either the eastern or western sides of the environment due to the low rms delay spread threshold (Figure 6.14 compared to Figure 6.18). As for the coverage area, the increase due to the addition of the third base station is not significant; it is just 7.13% for the receivers' positions having a guaranteed service.

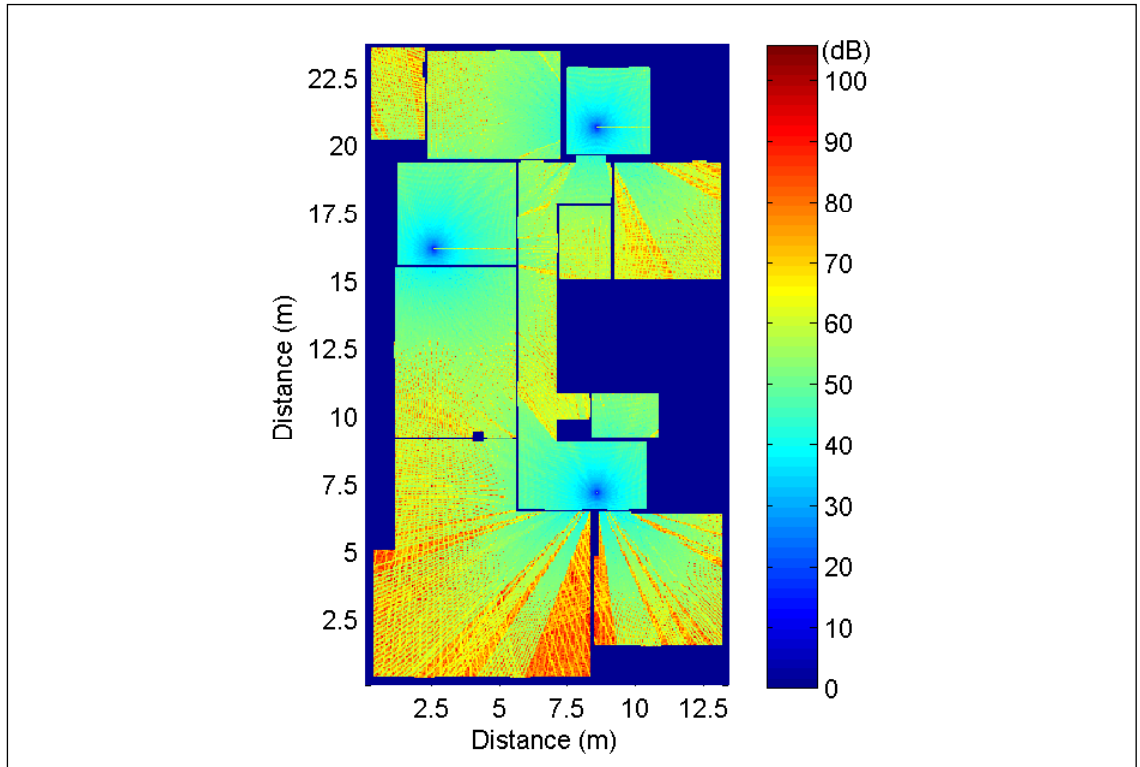


Figure 6.18: Path loss in dB at the possible receivers' positions throughout the empty environment for three transmitters with coordinates of (8.675, 7.225), (2.675, 16.225) and (8.675, 20.725)

In addition, the maximisation of equation 6.3 as well as that of equation 6.5 with higher priority given to the path loss values ($\alpha=0.7$) produces the same optimal positions with coordinates (8.675, 4.225), (2.675, 16.225) and (8.675, 20.725). The guaranteed coverage percentage they provide is 49.25% in addition to 29.74% of uncertain

coverage. Consequently, the addition of a third base station has increased the guaranteed coverage by 15.02%.

On the other hand, when higher priority is given to the rms delay spread values in the maximisation of equation 6.5 ($\alpha=0.2$), the number of receivers' positions having their rms delay spread less than 30 ns is increased, though this is meaningless unless the corresponding path loss is less than 60 dB. The resultant guaranteed coverage is 40.73% compared to 35.18% for the two transmitters' case. As for the risky service percentage it has hardly changed (0.08% increase).

6.6 Conclusions

In this chapter, the optimisation of base stations' locations within an indoor environment was presented. Unlike the work available in the literature that ignores the time dispersion parameters, the objective functions are defined based on the path loss as well as the rms delay spread values. Three objective functions are defined. The first maximises the number of receivers' positions that have their path loss and rms delay spread less than predefined thresholds. The second maximises the receivers' positions having their path loss less than the threshold regardless of the rms delay spread while giving higher priority to these having the path loss and rms delay spread less than the thresholds. The third cost function maximises the number of receivers' positions having the path loss less than the corresponding threshold in addition to the number of receivers' positions having the rms delay spread less than the threshold independently and each is scaled by a trade-off factor that specifies which parameter must influence the cost function more. As a receiver's position with low rms delay spread and high path loss compared to the thresholds do not enjoy service, it is recommended to give higher priority to the path loss values thus to select the trade-off factor to be higher than 0.5. In this way, higher coverage will be attained when the base stations are placed at the resulting optimal positions. Note that the threshold values are selected based on the receiver's sensitivity, the amount of emitted power and the symbol rate.

It is demonstrated that the inclusion of the rms delay spread to the cost function affects the optimal base stations' positions and hence this parameter cannot be ignored especially with higher data rate systems.

When the environment is considered to be empty and for low bit rate systems (threshold 400 ns), all the receivers' locations have their rms delay spread values less than the threshold. When the objective function is defined based on the time dispersion parameter only, any transmitter's position can be considered optimal whereas when the cost function is defined based on both, the path loss and rms delay spread, the optimal base station's location is controlled by the path loss values only and the different forms of the objective functions become equivalent.

When the rms delay spread threshold is lowered, the rms delay spread starts to control the optimal base station's location along with the path loss values. The optimal location is shifted away from central locations into the sides of the environment. In this way, the emitted rays have to travel longer distance and get more attenuated before being reflected back which will lower the number of reflections rays may encounter and decreases the rms delay spread values. Whereas when the path loss threshold is decreased, the base station moves toward wide areas with least obstacles. In this way the area with high field strength, mainly found around the base station, is increased.

Concerning the coverage, as the threshold values are decreased, the coverage area decreases and a single base station will not be enough to serve the environment and additional base stations are needed. Comparing the effect of adding a second and a third base station, higher increase in the coverage is achieved after adding the second one. In addition, when base stations are placed adjacent to each other, the receivers' allocation is interleaved whereas when they are far from each other the allocation is in big blocks with few positions interleaved within the blocks.

For most cases, the maximisation of equations 6.1 and 6.3 gives the same optimal positions. When they are not, the optimal positions obtained based on the latter equation provide less guaranteed service area but higher overall coverage (guaranteed and risky service). In case the receivers' positions within the uncertain coverage area have their rms delay spread values very close to the threshold they get a slightly disturbed service leading to an overall covered area higher than that obtained by placing the base stations at the optimal positions obtained based on equation 6.1. However, if the rms delay spread values are far from the threshold, it would be better to place the base stations based on the maximisation of equation 6.1 and get higher guaranteed service area. Consequently, the decision of which cost function to use is dependent on

how severe the rms delay spread values are which depends on the form and constituent of the environment and how higher the guaranteed coverage that the optimisation of the cost function of equation 6.1 is providing compared to that of equation 6.3. In addition, the maximisation of equation 6.5 with trade-off factor of 0.7 leads to either the optimal base stations' positions obtained when equation 6.1 or equation 6.3 are used, hence this trade-off is reasonable to include the time dispersion parameter without making the path loss values dominant.

Finally, the software sets the rms delay spread of a receiver's location not getting any ray to be 0 ns. In this case, a 0 ns rms delay spread means either a single ray or no ray reaching a certain receiver's location. This does not affect the maximisation of the cost functions of equations 6.1 and 6.3 as these cost functions take into account the receivers' locations getting a signal with path loss below a predefined threshold. Consequently, a receiver's location not receiving any ray is not added to the cost functions' calculation. On the other hand, this may affect the maximisation of equation 6.5 with the trade-off set to 0. In this case, the cost function counts the number of receivers' having their rms delay spread lower than the threshold. The maximum number of receivers' locations satisfying this criterion is then obtained when the base stations are located at the sides of the environment such that more receivers' locations either get a single ray or no ray. As soon as the trade-off factor is increased, the effect of receivers' locations not getting any ray is reduced until it vanishes when the trade-off becomes greater than 0.5. Note that even if the receivers' locations not receiving any ray are not counted by the cost function of equation 6.5, the resulting optimal base stations' locations will lead to a big number of receiver's locations getting a single ray. This will reduce the coverage, therefore, a trade-off factor less than 0.5 is not recommended.

Chapter 7: Effect of Environment Changes on The Optimal Base Stations' Positions based on Rms Delay Spread and Path Loss values

7.1 Introduction

In the design stage, the furniture distribution and materials are most likely to be unknown and the optimal base stations' locations will be selected based on an empty environment. However, as the environment is furnished, the signal emitted from the base stations that are supposed to be at the optimal locations will bounce back and forth as it hits the furniture and the signal distribution will be different from that when the environment is empty and consequently the optimisation process must be redone to check how the optimal base stations' locations are affected.

Three different environment configurations are examined in this chapter. The first is when the environment is furnished with all windows and doors closed; it will be denoted the closed environment. The second differs from the first one by having the windows and almost all the doors open (denoted as the open environment) whereas in the third one people are added to the first environment configuration (denoted the environment with people). The three environments are initially considered to be served by a single base station. The three cost functions defined in chapter 6 are maximised for the same parameters' sets previously used with the empty environment. The optimal positions obtained based on each cost function are compared for the different environment configurations.

With the intention of increasing the coverage area within the environment with its various configurations, multiple base stations (two and then three base stations) are assumed to serve the environment and the three cost functions will be maximised accordingly. The effect of the environment changes on the optimal base stations' positions as well as the effect of using multiple base stations on the coverage percentage will be discussed. The co-channel interference was neglected as mentioned in chapter 6. The chapter will also discuss the effect of the cut-off power level selection as well as the antenna polarisation on the optimisation process.

In order to show that the results that will be discussed in this chapter are not specific to the test environment used, another indoor environment has been studied. This is first considered empty. Furniture is then added to the environment and some

environment changes are modelled. The optimal positions are found based on the cost functions defined in chapter 6 and the results are summarised in Appendix B.

7.2 Effect of Environment Changes On Single Transmitter's Location Optimisation

In this section, the indoor environment in its various forms is assumed to be served by a single base station. The optimal base station's positions results obtained after the maximisation of equations 6.1, 6.3 and 6.5 will be presented and the effect of environment changes on the optimal base station's positions will be discussed.

7.2.1 The Optimal Base Stations' Locations Results Based on Equation 6.1

The objective function to be considered first is that of equation 6.1. The optimisation of this cost function maximises the number of receivers' positions having the path loss and rms delay spread below predefined thresholds so that they enjoy the service. The four combinations of thresholds previously used when the environment was considered to be empty in chapter 6 will be utilised but with the various environment's configurations.

Firstly, the path loss and rms delay spread thresholds are set to 90 dB and 400 ns. The optimal position's coordinates obtained when the environment is considered empty are (4.175, 10.225). This position provides 91.31% guaranteed coverage in the empty environment. However, when the environment is filled with furniture with all doors and windows closed and based on the 2D ray tracing results, the coverage drops to 60.78%. When the windows and most of the doors are open, the coverage becomes 59.18% and when people are added to the closed environment the coverage is 58.34%. Figure 7.1 shows the path loss distribution over the environment for the different environment's configurations when the base station is placed at the optimal position obtained based on the empty environment. Compared to that in the empty environment, it is clear that the signal is more attenuated and a very low signal level travels toward the northern and southern parts of the environment. The furniture are acting as obstacles preventing the signal to travel directly to both ends of the environment, thus higher path loss values are obtained and less coverage percentage is achieved.

It is most probable that the optimal base station's coordinates obtained when the environment is considered empty change once the environment configuration changes. After optimising the objective function with thresholds set to 90 dB and 400 ns, the result is the same for the three different environment's configurations though different from that of the empty environment. The base station is moved into the corridor in the centre of the environment. The coordinates are (7.175, 11.725) and Figure 7.2 shows the corresponding path loss distribution in the closed environment. The new certain coverage values are 71.52%, 70.31% and 70.33% for the closed environment, open environment and the environment with people respectively. Note that the percentage of receivers' positions having their path loss less than 400 ns is not 100% like in the case of the empty environment but it is around 99% for the optimal position thus the rms delay spread values are affecting the optimisation but the path loss values are still the dominant parameter in the optimisation as the rms delay spread threshold is considered high. This will be discussed further when the optimisation of equation 6.5 is explained later in this chapter. Note that the receivers' locations with rms delay spread higher than 400 ns are mainly around the places with metallic objects where the signal can bounce back and forth multiple times before attenuating which increases the rms delay spread.

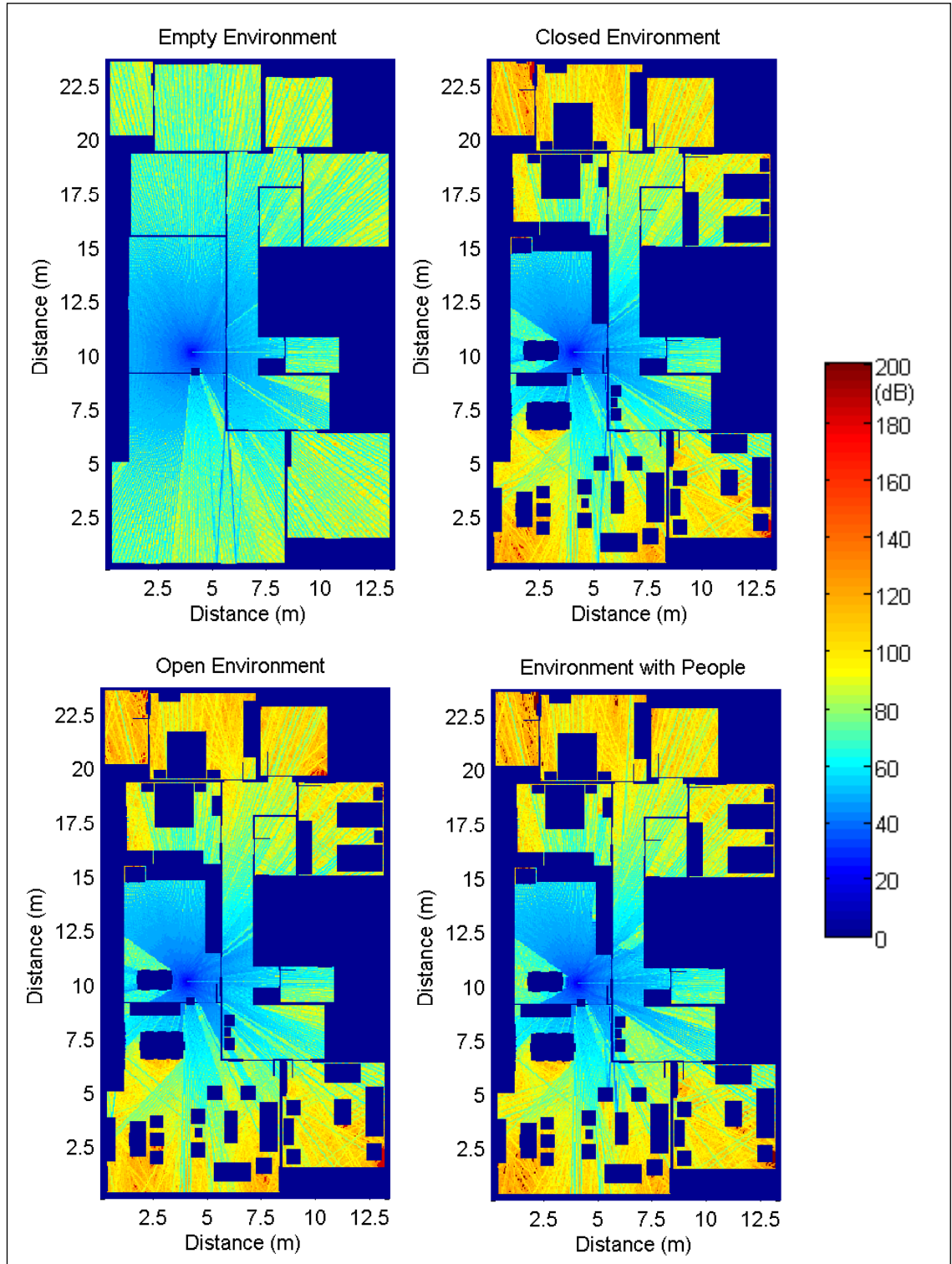


Figure 7.1: Path loss in dB at the possible receivers' positions throughout the four environment's configurations for a single transmitter with coordinates of (4.175, 10.225)

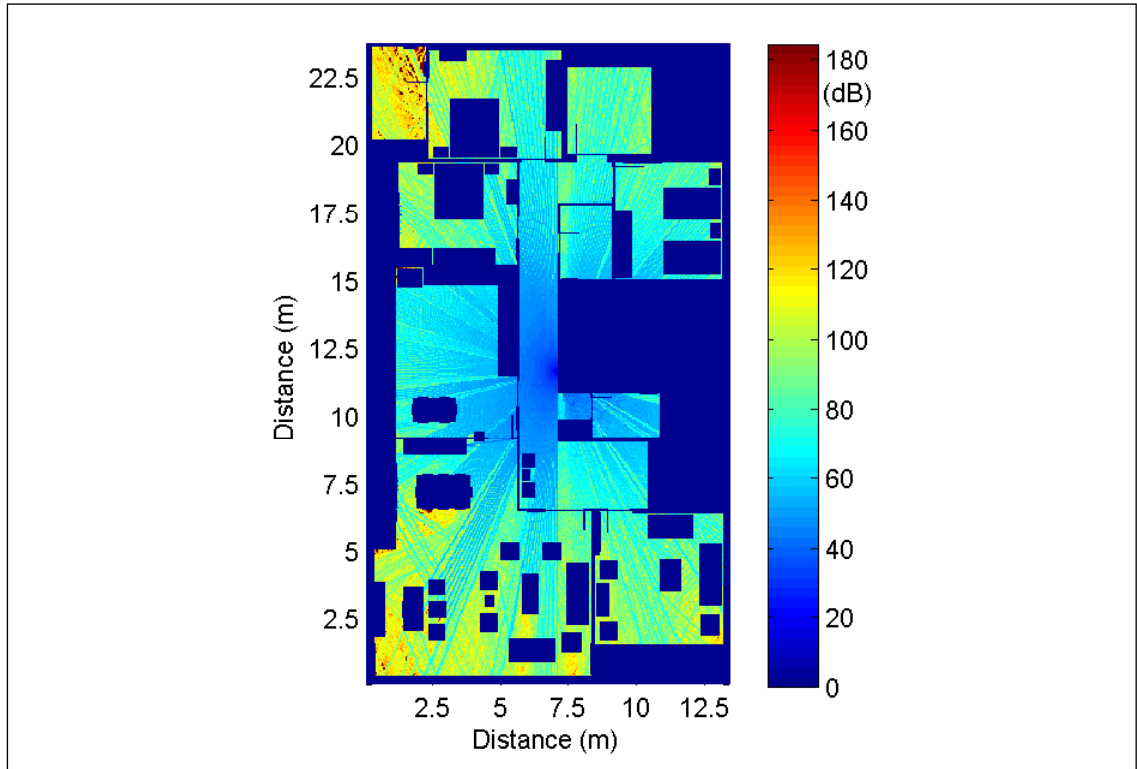


Figure 7.2: Path loss in dB at the possible receivers' positions throughout the closed environment for a single transmitter with coordinates of (7.175, 11.725)

Similarly, when the rms delay spread threshold is lowered to 30 ns while the path loss threshold is kept at 90 dB, the optimal position is sensitive to the environment changes. If the base station is kept at the optimal position obtained with the empty environment, the coverage in the closed environment is 61.19%. As for the open environment and the environment with people, it is 60.81% and 58.67% respectively. Moving the base station into its corresponding optimal position obtained after repeating the optimisation process, taking into account the changes in the environment, increases the coverage to 65.67% in the closed environment, 65.21% in the open environment and 62.22% in the environment with people. The optimal base stations' coordinates for all the threshold combinations are summarised in Table 7.1.

In addition, as the rms delay spread threshold is lowered to 30 ns, the optimal positions of the three environment's configurations moved away from the corridor. This is because the signal is reflected back and forth many times along the corridor which increases the rms delay spread values there. For (7.175, 11.725) base station's location, the 400 ns was high and almost all the receivers' positions have their rms delay spread values lower than the threshold. When the threshold is brought to 30 ns, the majority of

locations in the corridor do not satisfy the threshold criterion and have their rms delay spread above 30 ns. This is shown in Figure 7.3. However, the area in the corridor has the lowest path loss which is not enough as both the path loss and the rms delay spread must be below the threshold knowing that the cost function is maximising the number of receivers' positions satisfying both conditions. Consequently, the optimal base station's position has moved to (5.675, 8.725) for the closed and open environments and to (8.675, 8.725) for the environment with people. The different location in the environment with people is mainly because of the presence of people blocking the signal from travelling further in the environment. Figure 7.4 shows the path loss in the closed environment as well as that in the environment with people when the base station is located at the optimal position of the closed environment. Note that the people's locations highly affecting the path loss are circled in red. The high path loss in these areas (mainly higher than 90 dB) lowers the coverage percentage and another base station is able to provide higher coverage.

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225)	(5.675, 8.725)	(5.675, 8.725)	(8.675, 8.725)
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	(8.675, 7.225)	(5.675, 10.225)	(5.675, 8.725)	(5.675, 10.225)

Table 7.1: Optimal base station's positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.1 for different parameters' values

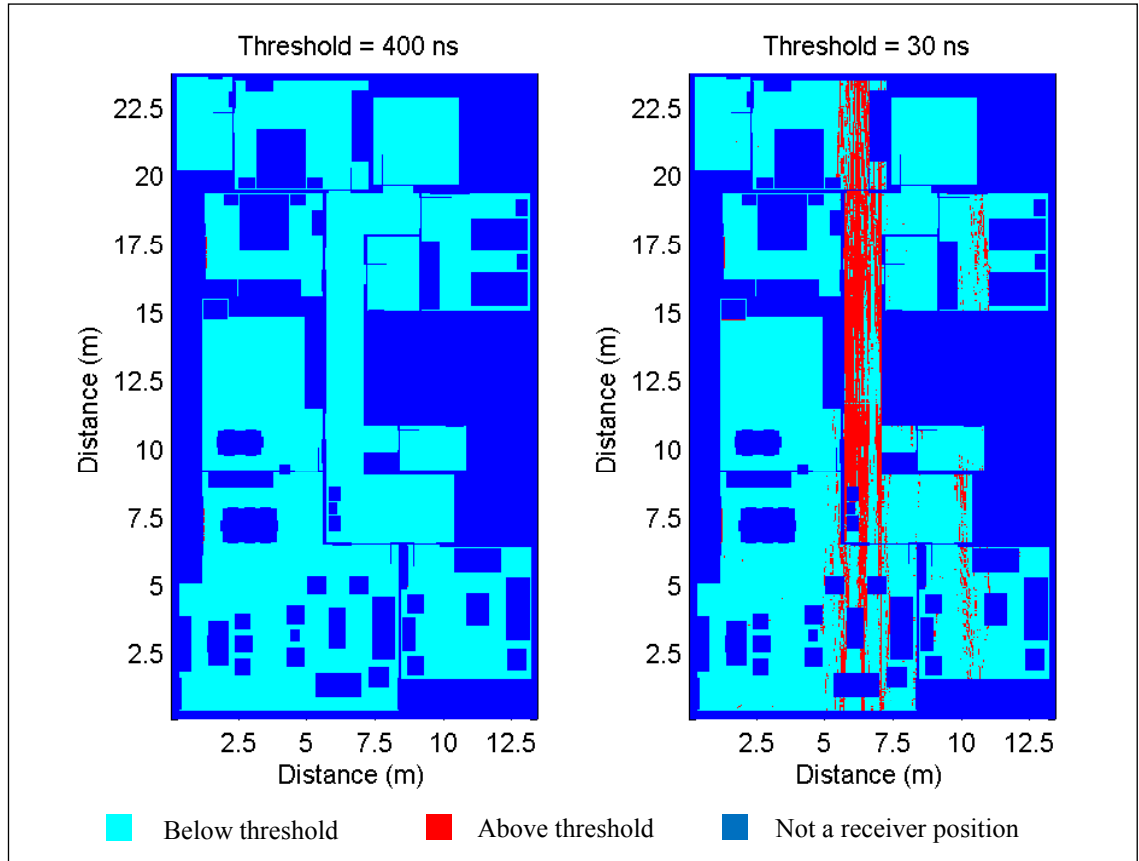


Figure 7.3: Positions having their rms delay spread below the threshold of 400 ns and 30 ns when the base station is located at (7.175, 11.725) in the closed environment

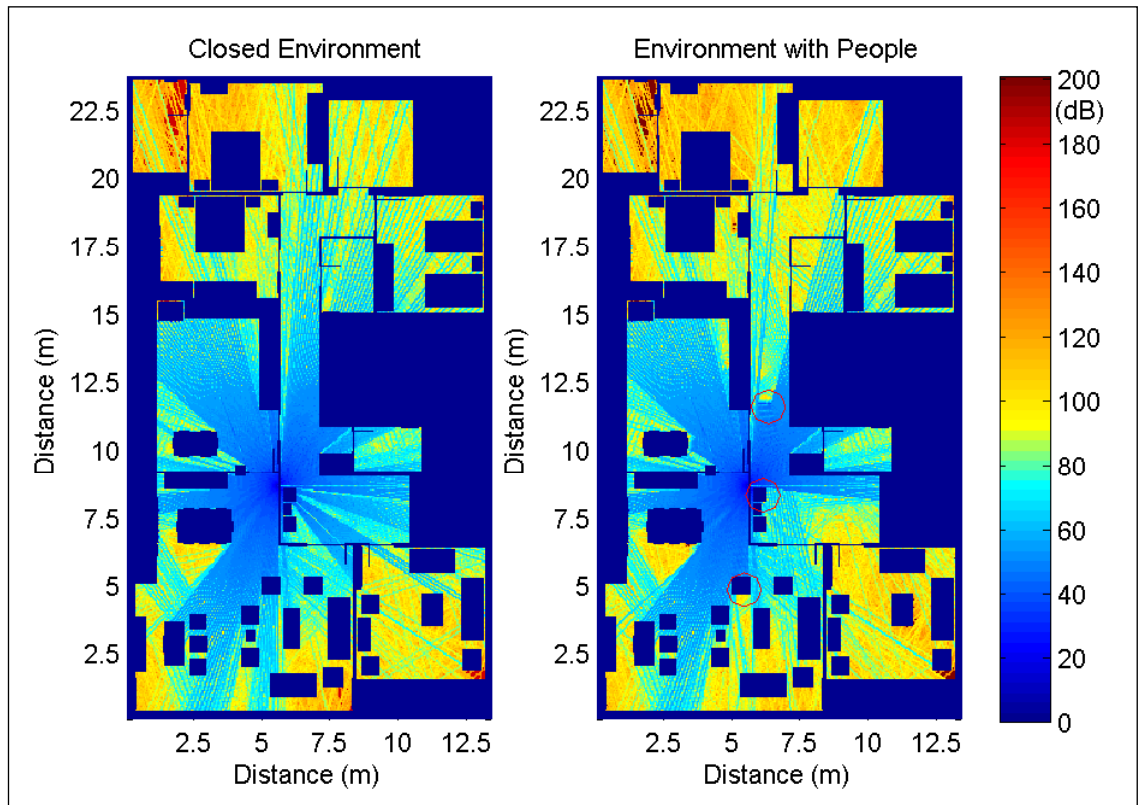


Figure 7.4: Path loss in dB at the possible receivers' positions throughout the closed environment and the environment with people for a single transmitter with coordinates of (5.675, 8.725)

The third set of thresholds used is 60 dB for the path loss and 400 ns for the rms delay spread. As the rms delay spread threshold is high, the main parameter controlling the optimisation is the path loss. As in all the above cases, the optimal position is repositioned when the environment is not empty anymore. The same optimal position with coordinates (7.175, 8.725) is obtained for the closed environment and the environment with people providing 26.1% and 24.63% coverage respectively. The path loss distribution throughout both environments is shown in Figure 7.5. The main person obstructing the signal is circled in red. For this case, the optimal position is not shifted to another place as the area mainly affected already lacks enough coverage and no other base station's location is able to offer better service. As for the open environment, the base station located at (7.175, 7.225) is able to provide 24.92% coverage.

In addition, it was previously mentioned in section 6.3.1 that when the path loss threshold is lowered from 90 dB to 60 dB while the rms delay spread is kept high, the optimal position moved to a wide area with least obstacles. As furniture is placed in the environment, the wide empty area where the base station was positioned at (5.675, 5.725) in the empty environment is no longer without obstacle and the base station is relocated into another wide area with least obstacles so that it can provide the biggest area with low path loss mainly less than the threshold of 60 dB.

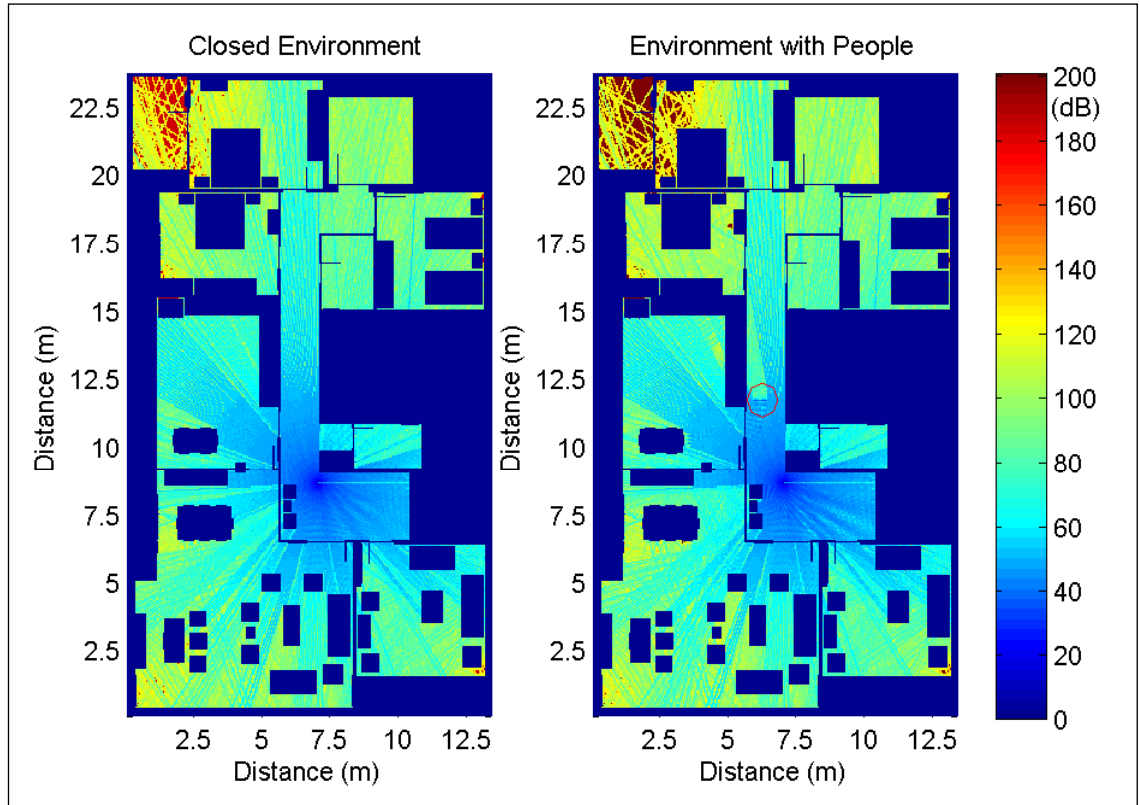


Figure 7.5: Path loss in dB at the possible receivers' positions throughout the closed environment and the environment with people for a single transmitter with coordinates of (7.175, 8.725)

The last threshold values discussed in this section are 60 dB for the path loss and 30 ns for the rms delay spread. Comparing the optimal position obtained in the empty environment with these obtained for the three other environment's configurations, different optimal positions are obtained (Table 7.1). When the base station is placed at its optimal location, 25.68%, 23.77% and 23.2% of the receivers' locations have guaranteed coverage in the closed environment, open environment and environment with people respectively. Concerning the uncertain coverage or in other words, the percentage of receivers' locations having their path loss less than the threshold with their rms delay spread higher than the threshold, it is less than 1% for the three environment's configurations. Therefore, almost all the receivers' positions with path loss less than 60 dB have their rms delay spread less than 30 ns. The uncertain coverage in the empty environment scenario was higher than that of the other environment's configurations. This is because the rms delay spread values in the empty environment are higher than those in a furnished environment. In an empty environment, a ray travels a long distance before it hits an object, mainly a door, a wall or a window which means longer time. As it has not hit many objects on its way, it is not highly attenuated and has

enough strength to bounce back and forth many times. Consequently, at a given receiver location, delayed rays will arrive creating a high rms delay spread. Whereas in a furnished environment, the ray will encounter lots of close obstacles and it will be reflected back faster. The ray will also die faster causing lower rms delay spread values. This is also the cause of lower path loss values and higher coverage for the empty environment compared to the other three environment's configurations. Assuming that the base station is located at (7.175, 11.725), which is not the optimal position for an rms delay spread threshold of 30 ns, the positions having the rms delay spread less than 30 ns are marked in cyan in Figure 7.6 inside the empty and closed environment. It is clear that for the same base station's position, the percentage of receivers' positions having the rms delay spread greater than 30 ns is much higher in the empty environment as opposed to the furnished environment (closed environment).

Note that for any configuration of the furnished environment, the maximum coverage obtained does not exceed three quarters of the possible receivers' positions and that was for the highest threshold explored. Multiple base stations are therefore needed to increase the coverage percentage even for high threshold values unlike the case of the empty environment where a single base station was able to provide service for almost all receivers' positions when high threshold values were used.

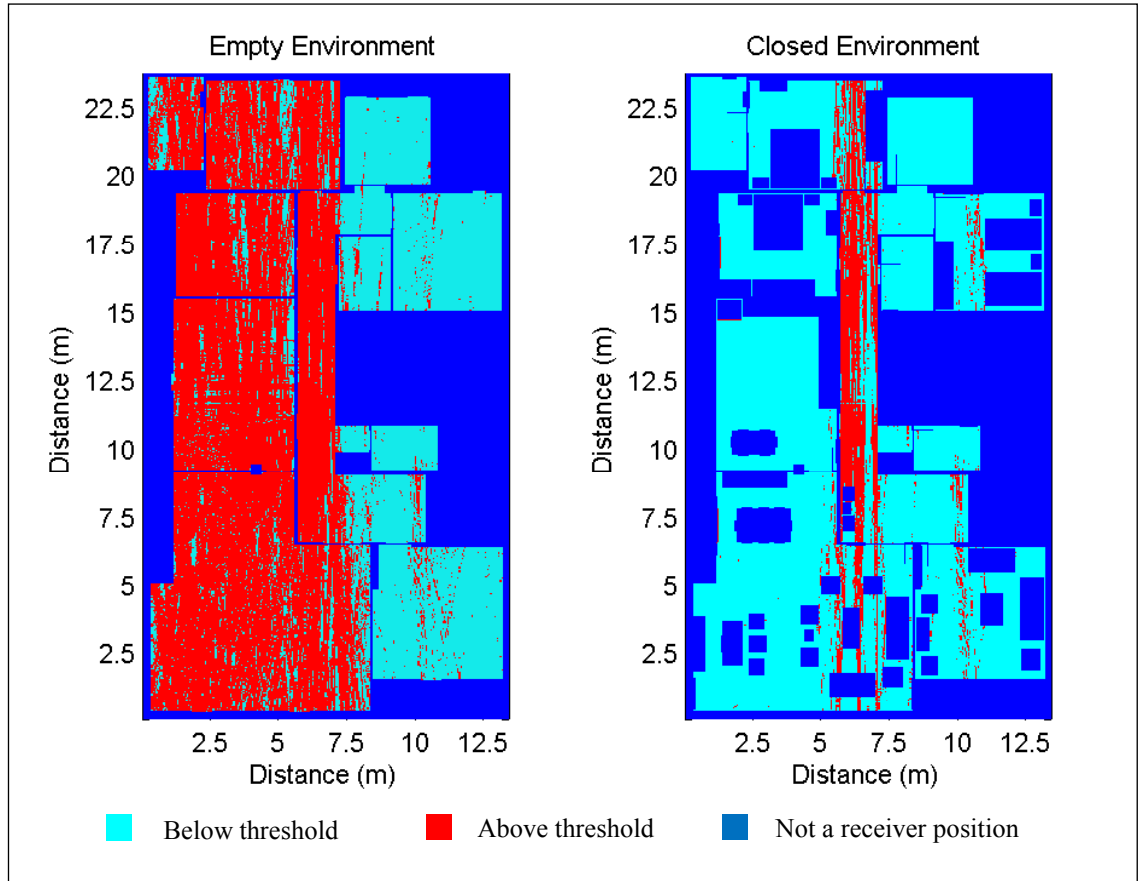


Figure 7.6: Receivers' positions having their rms delay spread below the threshold of 30 ns when the base station is located at (7.175, 11.725) in the empty and closed environments

7.2.2 The Optimal Base Stations' Locations Results Based on Equation 6.3

The optimisation of equation 6.3 maximises the number of receivers' positions having the path loss lower than a predefined threshold regardless of their rms delay spread values while giving higher priority to the receivers' positions having both the path loss and rms delay spread less than the thresholds. When the empty environment was considered in chapter 6, it was noticed that in most cases, the maximisation of equations 6.1 and 6.3 gives the same optimal positions with a few exceptions. The same issue took place when the closed and open environments as well as the environment with people are considered. The optimal base station's coordinates for various threshold values are shown in Table 7.2 with the coordinates that are different from these obtained based on the objective function defined in equation 6.1 underlined.

Starting with the 90 dB and 30 ns thresholds, the base station is relocated in the open environment and the environment with people when the objective function of

equation 6.3 is used instead of that of equation 6.1. For both environment configurations, the optimal position moved to the corridor of the environment at (7.175, 11.725). As explained in section 7.2.1, when the base station is placed in the corridor more receivers' locations have low path loss (lower than 90 dB). When the rms delay spread threshold is set to 400 ns, this position is the optimal. As the rms delay spread threshold is lowered to 30 ns, most receivers' positions in the corridor get their rms delay spread higher than the threshold. The function of equation 6.1 aims to maximise the receivers' locations with both criteria satisfied thus the position (7.175, 11.725) cannot be considered optimal. However, the corridor position at (7.175, 11.725) is able to maximise equation 6.3 as this equation tolerates receivers' positions satisfying the path loss criterion alone though with low priority.

The second set of thresholds where the two cost functions ended up with different optimal base station's locations is that of 60 dB and 30 ns. The change is for both the empty (discussed in section 6.3.3) and the open environment. The optimal position obtained based on the maximisation of equation 6.1 provides 23.33% overall coverage of which 22.73% is guaranteed whereas the position obtained based on the maximisation of equation 6.3 provides 24.92% overall coverage of which 21.19% is guaranteed.

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225)	(5.675, 8.725)	<u>(7.175, 11.725)</u>	<u>(7.175, 11.725)</u>
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	<u>(8.675, 4.225)</u>	(5.675, 10.225)	<u>(7.175, 7.225)</u>	(5.675, 10.225)

Table 7.2: Optimal base station's positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.3 for different parameters' values

7.2.3 The Optimal Base Stations' Locations Results Based on Equation 6.5

In this section, the objective function to be examined is that of equation 6.5. This cost function treats the receivers' positions with path loss less than a predefined threshold and these with rms delay spread less than a predefined threshold independently. The influence of each parameter on the cost function is specified based on the selection of the trade-off factor. Table 7.3 summarises the optimal base station's positions obtained for different thresholds as well as different trade-off factor values. The optimal base station's positions obtained in the empty environment are always different from those obtained in the other three environment's configurations. Compared with the closed environment, the optimal positions obtained in the open environment and the environment with people may or may not be identical. This depends on how much the path loss and rms delay spread distributions are affected due to the environment change with respect to the corresponding threshold values.

When the trade-off factor is set to 0, the cost function depends on the rms delay spread values only and the optimal base station's positions obtained in the three environment's scenarios are next to walls on either the west or east sides of the environment. This applies for both low and high threshold values unlike the empty environment's scenario, where for high rms delay thresholds, any base station's position can be considered optimal. When the base station is located on the sides of the environment, many receivers' locations acquire low field strength, mainly a single ray that leads to zero rms delay spread. This will lower the receivers' positions with rms delay spread higher than the threshold but will highly decrease the coverage. Consequently, the rms delay spread should not be used alone to find the optimal base station's position.

When the rms delay spread threshold is high, all the cost functions converge to the same optimal position regardless of the trade-off factor value (except 0) of equation 6.5. On the other hand, for low rms delay spread threshold with the trade-off set to 0.2, the optimal position provides reasonable coverage though lower than that obtained with higher trade-off factor or when the base station is positioned at the optimal position obtained when the other two cost functions are maximised. Furthermore, the maximisation of the cost function with trade-off equals to 0.7 gives the same optimal positions obtained when either equation 6.1 or 6.3 are optimised (when the two equations 6.1 and 6.3 give different optimal positions, the optimal positions of equation 6.5 are mainly equal to those of equation 6.3) and this was discussed in sections 7.2.1 and 7.2.2.

		Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	$\alpha=0$	Any position	(1.325, 7.225)	(1.325, 7.225)	(1.175, 1.225)
	$\alpha=0.2$	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
	$\alpha=0.7$	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
	$\alpha=1$	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
$PL_{th}=90$ dB $DL_{th}=30$ ns	$\alpha=0$	(11.675, 16.225)	(2.675, 20.725)	(10.175, 22.225)	(2.675, 20.725)
	$\alpha=0.2$	(8.675, 7.225)	(5.675, 10.225)	(5.675, 8.725)	(5.675, 10.225)
	$\alpha=0.7$	(8.675, 7.225)	(5.675, 8.725)	(7.175, 11.725)	(7.175, 11.725)
	$\alpha=1$	(4.175, 10.225)	(7.175, 11.725)	(7.175, 11.725)	(7.175, 11.725)
$PL_{th}=60$ dB $DL_{th}=400$ ns	$\alpha=0$	Any position	(1.325, 7.225)	(1.325, 7.225)	(1.175, 1.225)
	$\alpha=0.2$	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)
	$\alpha=0.7$	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)
	$\alpha=1$	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	$\alpha=0$	(11.675, 16.225)	(2.675, 20.725)	(10.175, 22.225)	(2.675, 20.725)
	$\alpha=0.2$	(8.675, 7.225)	(5.675, 10.225)	(5.675, 17.725)	(5.675, 10.225)
	$\alpha=0.7$	(8.675, 7.225)	(5.675, 10.225)	(5.675, 8.725)	(5.675, 10.225)
	$\alpha=1$	(5.675, 5.725)	(7.175, 8.725)	(7.175, 7.225)	(7.175, 8.725)

Table 7.3: Optimal base station's positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.5 for different parameters' values

7.3 Effect of Environment Changes On Two Transmitters' Locations Optimisation

Based on the coverage percentage achieved when a single base station is assumed to be serving the environment, there is a need for additional base stations in order to improve the coverage percentage. Unlike the empty environment where for high threshold values a single transmitter is enough to provide high coverage throughout the environment, extra base stations are needed in the furnished environment with its different configurations. This section will discuss the optimal locations of two base stations within the three furnished environment's configurations as well as the effect of the additional base station on the coverage.

7.3.1 The Optimal Base Stations' Locations Results Based on Equation 6.1

The maximisation results of equation 6.1 when two transmitters are assumed to serve the environment with its different configurations are presented in this section. Considering the thresholds of 90 dB and 400 ns, the two base stations optimal positions' coordinates obtained for the three environment's configurations are the same at (5.675, 5.725) and (5.675, 19.225). One of the base stations is located at the same place as that in the empty environment while the second is at a different place. Figure 7.7 shows the path loss over the empty and closed environments when the two base stations are located at (7.175, 4.225) and (5.675, 19.225) which are the optimal positions of the empty environment. It is clear that as the environment is furnished, the base station at (7.175, 4.225) is surrounded by objects reducing the signal strength and preventing the signal from travelling farther in the environment. As for the second base station, the blocking effect is weaker thus only the base station at (7.175, 4.225) is relocated outside the loop of objects. The path loss distribution over the closed environment when the two base stations are placed at their corresponding optimal locations is shown in Figure 7.8.

Concerning the guaranteed coverage percentage, the use of two base stations has increased it to 92.23% in the closed environment, 92.14% in the open environment and 91.23% in the environment with people while it was less than 75% for the three environment's configurations when a single base station was used. As for the percentage of receivers' locations with uncertain coverage, it is just 0.06% or less for the different environment's configurations. This is because almost all the receivers' locations have their rms delay spread below 400 ns.

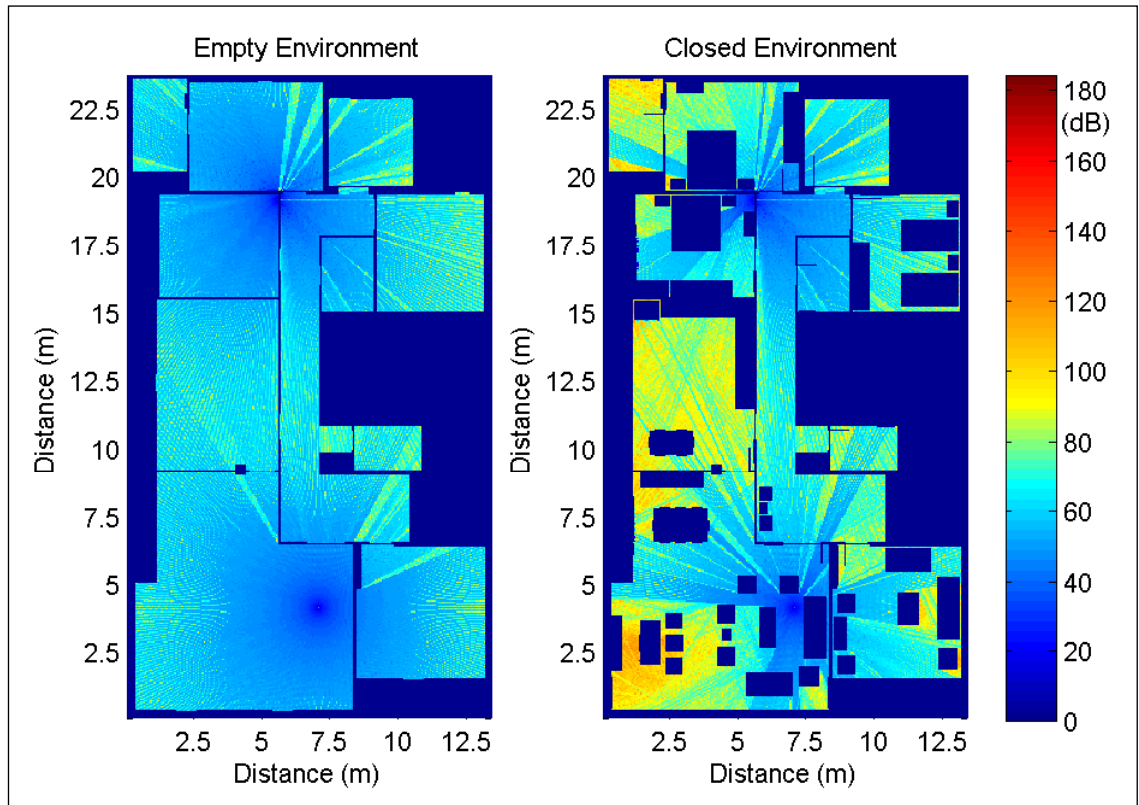


Figure 7.7: Path loss in dB at the possible receivers' positions throughout the empty and closed environments for two transmitters with coordinates of (7.175, 4.225) and (5.675, 19.225)

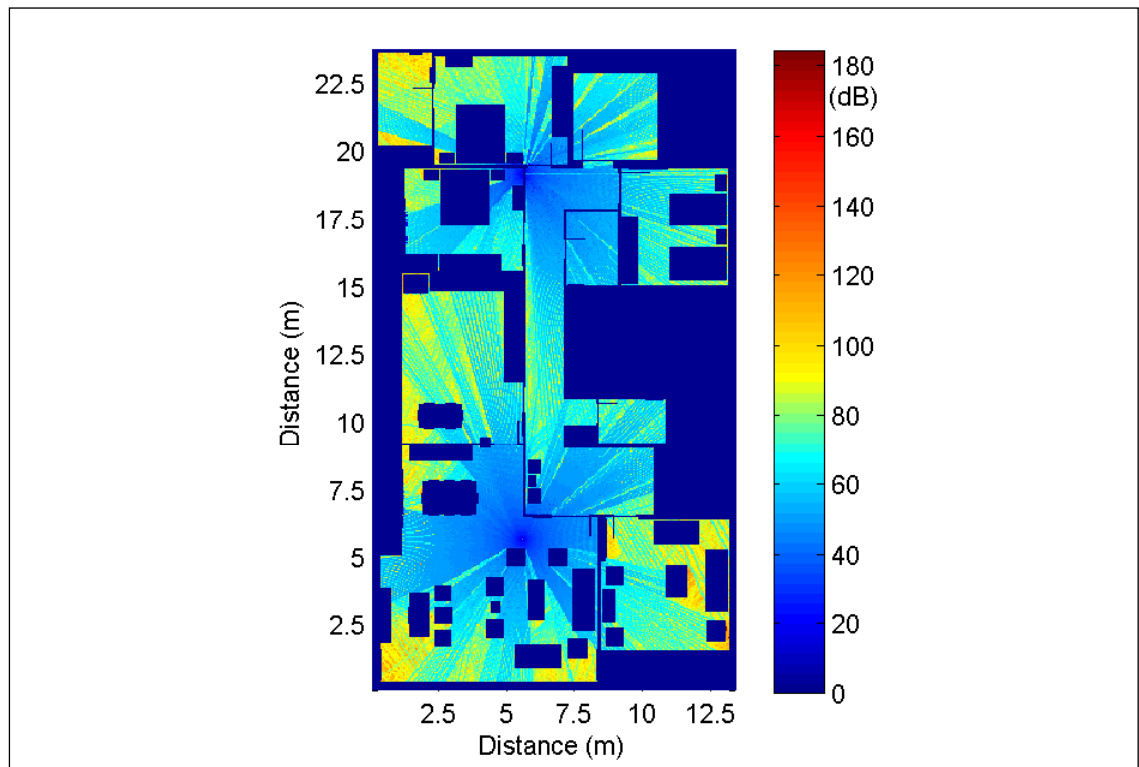


Figure 7.8: Path loss in dB at the possible receivers' positions throughout the closed environment for two transmitters with coordinates of (5.675, 5.725) and (5.675, 19.225)

In addition, when the rms delay spread threshold is lowered to 30 ns, the optimal base stations' locations of the closed, open and empty environments have not changed though the coverage was slightly decreased to 90.94%, 90.26% and 90.31% respectively. The optimal positions did not change after lowering the threshold to 30 ns as the percentage of positions with rms delay spread less than the threshold has decreased by less than 2% for the various environment's configurations.

Trying to keep the base stations at their optimal positions obtained for the empty environment after maximising the cost function with thresholds of 60 dB and 400 ns in the closed environment, open environment or environment with people ends up having the base stations surrounded by objects which lower the signal level. Consequently, the base stations are relocated keeping in mind that when the path loss threshold is low, the base station positions in a wide area with least obstacles. Furthermore, the coverage percentage is 47.45% in the closed environment, 45.82% in the open environment and 46.17% in the environment with people when two base stations are used while it was 26.1%, 24.92% and 24.63% respectively with a single base station. The optimal positions for each environment scenario for various threshold values are shown in Table 7.4.

Similarly, the base stations are repositioned when the environment is furnished and the thresholds are set to 60 dB and 30 ns (Table 7.4). The additional base station has increased the guaranteed coverage percentage to 46.02%, 41.61% and 44.24% in the closed environment, open environment and the environment with people respectively. Recalling that the uncertain coverage is where the receiver's position has the path loss less than the threshold with the rms delay spread greater than the corresponding threshold, the uncertain coverage used to increase when the rms delay spread threshold is lowered to 30 ns as less receivers' positions satisfy the rms delay spread criterion. However, for the furnished environment with its different forms and for the same rms delay spread threshold (30 ns), the uncertain coverage area hardly exists. This is because in the furnished environment lower rms delay spread values are obtained compared to the empty environment as explained in section 7.2.1.

In order to compare the rms delay spread values between the empty and furnished (closed) environment, two base stations' locations are selected, one down on the south west side of the environment at (4.175, 2.725) and the other around the centre

of the environment in the corridor at (7.175, 11.725) and the histogram of the rms delay spread values is plotted (Figure 7.9). The rms delay spread values in the closed environment reach a value around 600 ns but with very low frequency (just few receivers' locations) mainly because of the presence of some metallic items that can reflect the signal multiple times without attenuating it. However, the highest frequency is for the rms delay spread values below 20 ns as can be seen in the zoomed-in version of the histograms of the closed environment in Figure 7.10. When the base station is positioned down on the south west side of the environment at (4.175, 2.725), a higher frequency is achieved for the 0 rms delay spread as the signal cannot travel far in the northern part of the environment and a lot of receivers' positions will receive a single ray which makes the rms delay spread equals 0. The number of receivers' positions with 0 rms delay spread decreases when the base station is moved to a central location. Regarding the empty environment, the maximum rms delay spread value is around 80 ns with few receivers' positions having their rms delay spread around 100 ns when the base station is placed at (7.175, 11.725) while the highest frequencies are for the values between 20 ns and 50 ns. Accordingly, based on the distribution of the rms delay spread, higher values are achieved in the empty environment though the maximum attained in the furnished environment is higher and when the rms delay spread threshold goes less than 30 ns, the time parameter will have higher influence on the cost function and bigger area with uncertain coverage will be present in the furnished environment.

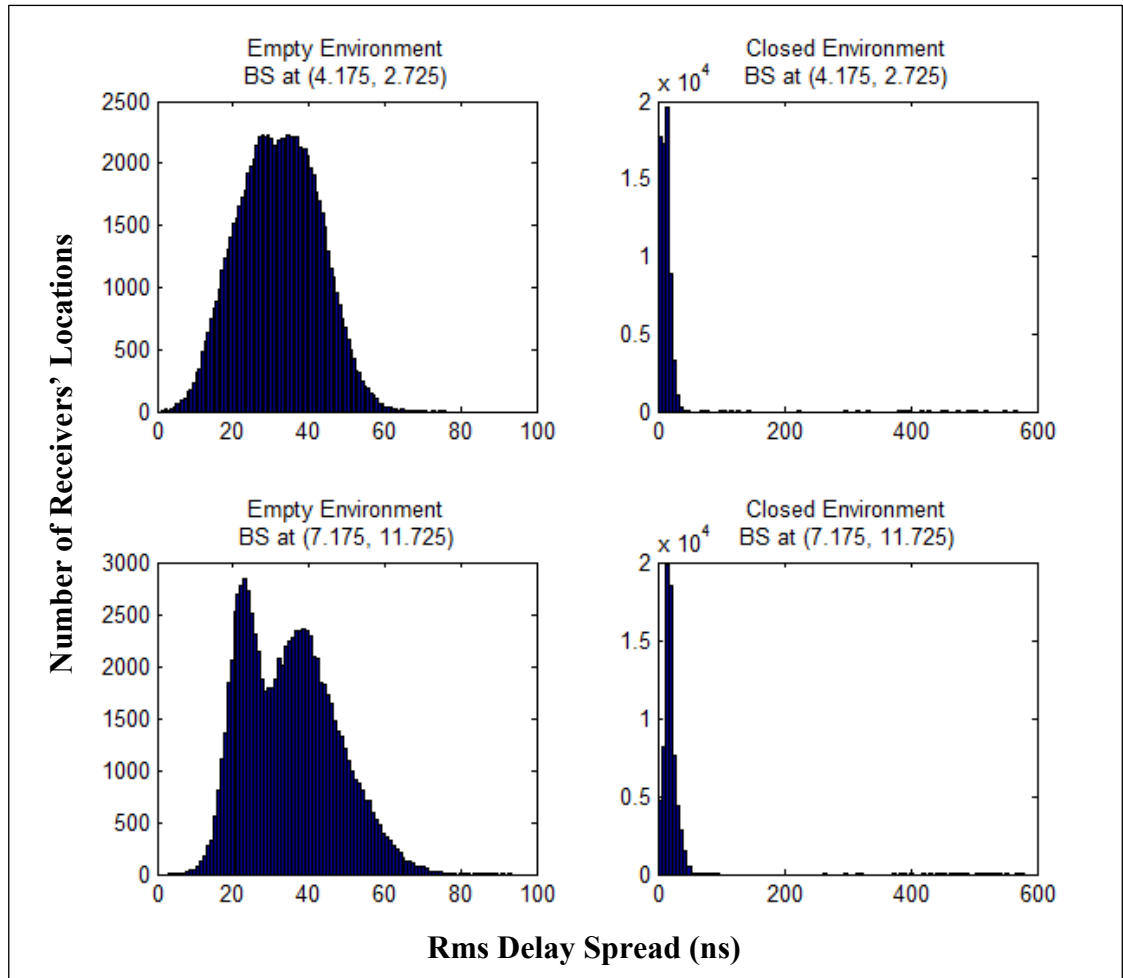


Figure 7.9: Histograms of rms delay spread in the empty and closed environments for two base station's locations at (4.175, 2.725) and (7.175, 11.725)

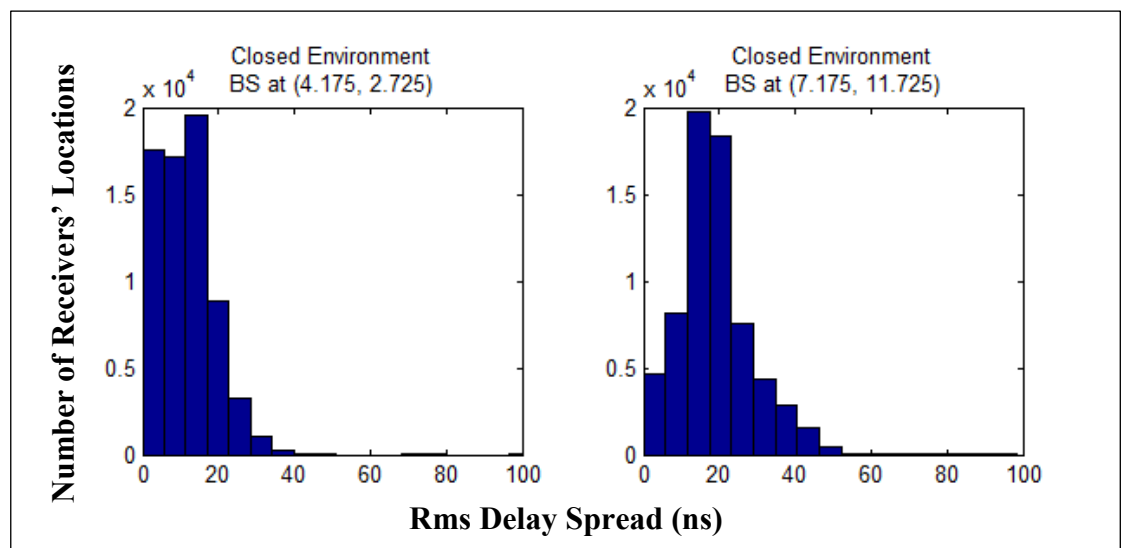


Figure 7.10: Zoomed-in version of the histograms of rms delay spread in closed environment for two base station's locations at (4.175, 2.725) and (7.175, 11.725)

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225) (11.675, 16.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	(8.675, 7.225) (8.675, 19.225)	(5.675, 10.225) (8.675, 19.225)	(5.675, 5.725) (5.675, 16.225)	(5.675, 10.225) (8.675, 19.225)

Table 7.4: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.1 for different parameters' values (2 base stations)

7.3.2 The Optimal Base Stations' Locations Results Based on Equation 6.3

The optimisation of equation 6.3 when the environment with its different configurations is assumed to be served by two base stations gives the same optimal positions obtained when equation 6.1 is used for most threshold values with the exception of the 60 dB and 30 ns thresholds in the empty and open environments. Table 7.5 presents a summary of the optimal coordinates with the ones that are different from that of equation 6.1 underlined. The optimal positions of the empty environment were previously discussed in section 6.4.3. In addition, comparing the optimal positions obtained for the open environment using equations 6.1 and 6.3 with thresholds 60 dB and 30 ns, it is noticed that although the optimal positions' coordinates of the later equation ((5.675, 7.225) and (7.175, 17.725)) provide higher percentage of positions with path loss less than 60 dB, they are not considered optimal for equation 6.1 because of some of the receivers' positions that do not satisfy the rms delay spread threshold.

The number of receivers' positions not satisfying the rms delay spread criterion is high enough to decrease the coverage percentage and allow another combination of base stations' positions ((5.675, 5.725) and (5.675, 16.225)) to provide higher guaranteed coverage. At the same time, this number of receivers' positions maximises equation 6.3 since it gives higher priority to receivers' positions that satisfy the path loss criterion alone.

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225) (11.675, 16.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	<u>(8.675, 4.225)</u> <u>(5.675, 17.725)</u>	(5.675, 10.225) (8.675, 19.225)	<u>(5.675, 7.225)</u> <u>(7.175, 17.725)</u>	(5.675, 10.225) (8.675, 19.225)

Table 7.5: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.3 for different parameters' values (2 base stations)

7.3.3 The Optimal Base Stations' Locations Results Based on Equation 6.5

The last optimal base stations' results to be discussed, when two base stations are serving the four environment's configurations, is that of equation 6.5. The results of the objective function's maximisation are shown in Table 7.6 for different thresholds

and different trade-off factors for the empty, closed and open environments as well as the environment with people.

The same observations discussed when this cost function is maximised with a single base station serving the environments (section 7.2.3) apply in the case of two base stations. The only thing to add is that for a trade-off factor of 0, the second base station is next to walls on either the west or east sides of the environment close to the first one but not adjacent as in the case of the empty environment.

		Empty Environment	Closed Environment	Open Environment	Environment with People
PL_{th}=90 dB DL_{th}=400 ns	$\alpha=0$	Any 2 positions	(1.175, 1.225) (1.325, 7.225)	(1.175, 1.225) (1.325, 7.225)	(1.175, 1.225) (1.175, 4.225)
	$\alpha=0.2$	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
	$\alpha=0.7$	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
	$\alpha=1$	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
PL_{th}=90 dB DL_{th}=30 ns	$\alpha=0$	(11.675, 16.225) (11.675, 17.725)	(13.175, 19.225) (2.675, 20.725)	(10.175, 20.725) (10.175, 22.225)	(13.175, 19.225) (2.675, 20.725)
	$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225)	(5.675, 4.225) (5.675, 17.725)	(8.675, 4.225) (5.675, 17.725)	(5.675, 5.725) (5.675, 19.225)
	$\alpha=0.7$	(8.675, 7.225) (11.675, 16.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
	$\alpha=1$	(7.175, 4.225) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)
PL_{th}=60 dB DL_{th}=400 ns	$\alpha=0$	Any 2 positions	(1.175, 1.225) (1.325, 7.225)	(1.175, 1.225) (1.325, 7.225)	(1.175, 1.225) (1.175, 4.225)
	$\alpha=0.2$	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)
	$\alpha=0.7$	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)
	$\alpha=1$	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)
PL_{th}=60 dB DL_{th}=30 ns	$\alpha=0$	(11.675, 16.225) (11.675, 17.725)	(13.175, 19.225) (2.675, 20.725)	(10.175, 20.725) (10.175, 22.225)	(13.175, 19.225) (2.675, 20.725)
	$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225)	(5.675, 10.225) (5.675, 17.725)	(8.675, 7.225) (5.675, 17.725)	(5.675, 5.725) (5.675, 16.225)
	$\alpha=0.7$	(8.675, 4.225) (5.675, 17.725)	(5.675, 10.225) (8.675, 19.225)	(5.675, 7.225) (7.175, 17.725)	(5.675, 10.225) (8.675, 19.225)
	$\alpha=1$	(5.675, 4.225) (5.675, 17.725)	(8.675, 7.225) (7.175, 17.725)	(5.675, 7.225) (7.175, 17.725)	(8.675, 7.225) (7.175, 17.725)

Table 7.6: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.5 for different parameters' values (2 base stations)

7.4 Effect of Environment Changes On Three Transmitters' Locations Optimisation

The use of a second base station has improved the coverage but not enough especially for the parameters' sets with low path loss threshold thus the use of a third base station may be needed. In this section, the optimal base stations' locations obtained for the various forms of the indoor environment using the three cost functions will be discussed along with the improvement that the third base station will add to the service.

7.4.1 The Optimal Base Stations' Locations Results Based on Equation 6.1

Starting with the maximisation of equation 6.1 with path loss threshold of 90 dB and rms delay spread threshold of 400 ns, different combinations of three base stations' coordinates are obtained for the various environment's configurations as shown in Table 7.7. Using three base stations placed at their optimal positions in the empty environment provides coverage almost all over the environment (99.98%), however, keeping the base stations at these locations in the closed environment for example, decreases the coverage to 94.33%. The main problem is that one of the base stations that is located at (7.175, 4.225) and serving the biggest area of the environment (41.29% of the possible receivers' locations) is encircled by objects which have stopped the service within the area in the south west corner of the environment. The corresponding coverage map is shown in the left plot of Figure 7.11 with the main area that lost the coverage circled. The solution of such a problem when the environment was served by either a single or two base stations ended up by the movement of the base station outside the circle of objects keeping the corners without coverage. However, for the three transmitters' scenario, the solution is to move the base station southward inside the loop of objects to position (5.675, 2.725) to provide coverage for the area in the south west corner. This is at the cost of less receivers' positions served by this base station, only 22.76%. As this base station was moved southward and is serving less receivers' positions the others have to relocate to fill the gaps it has caused. Figure 7.12 shows the receivers' allocation toward each base station before and after the three base stations are relocated. The second plot of Figure 7.11 shows the coverage area when the base stations are repositioned to the optimal locations corresponding to the closed environment. The new coverage is 97.11%.

Based on the same context, the base stations are relocated into their new optimal positions though to different places in the open environment and environment with people (Table 7.7) with coverage 97.18% and 96.53% respectively.

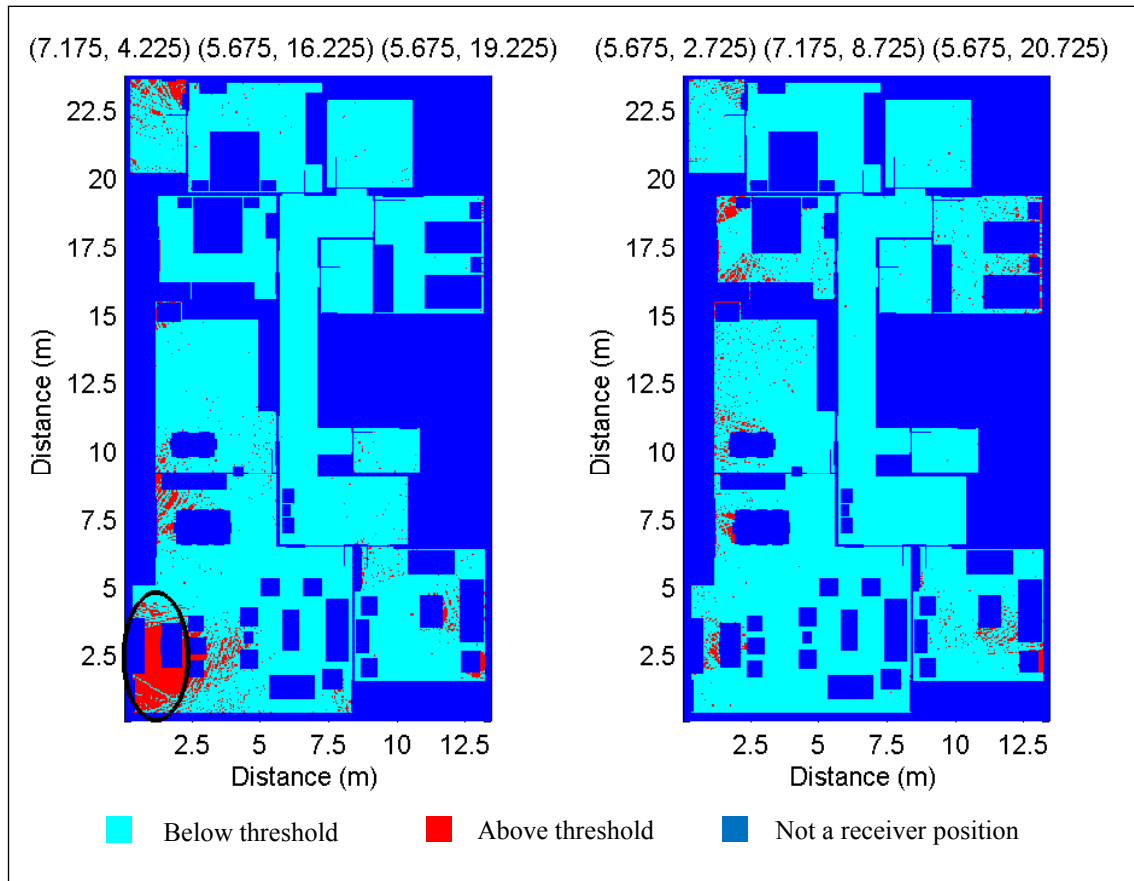


Figure 7.11: Receivers' positions having their path loss and rms delay spread below the thresholds of 90 dB and 400 ns when the three base stations are located at (7.175, 4.225), (5.675, 16.225), (5.675, 19.225) and (5.675, 2.725), (7.175, 8.725), (5.675, 20.725) in the closed environment

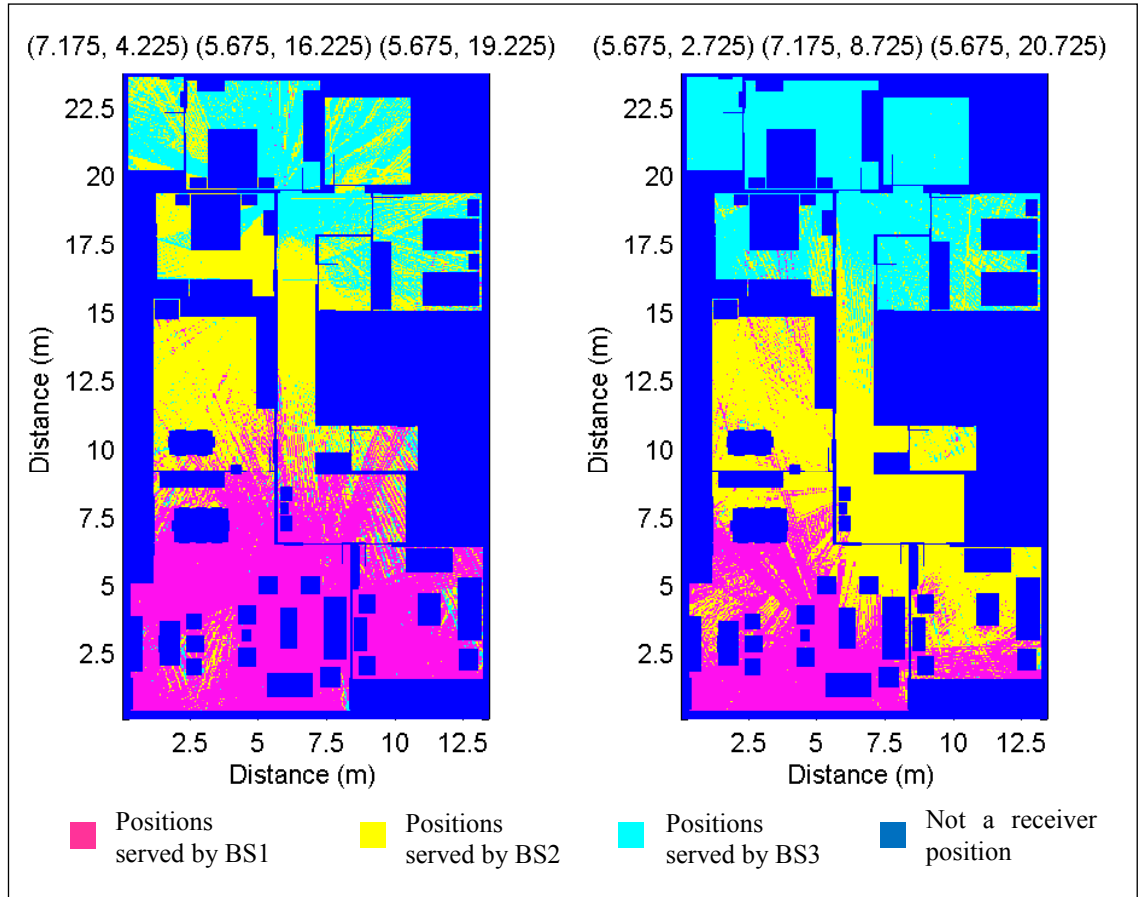


Figure 7.12: Receivers' allocation into the base stations BS1, BS2 and BS3 with coordinates (7.175, 4.225), (5.675, 16.225), (5.675, 19.225) and (5.675, 2.725), (7.175, 8.725), (5.675, 20.725) respectively, in the closed environment

On the other hand, when the rms delay threshold is reduced to 30 ns, that is when the symbol rate is increased, two of the base stations' locations obtained in the empty environment cannot be placed in the three other environment's configurations due to the presence of objects. Furthermore, if the base stations are kept at the optimal positions obtained when the thresholds were 90 dB and 400 ns, 6.48%, 2.61% and 8.27% of the receivers' locations will correspond to the regime of risky service because their rms delay spread values turn out to be less than the threshold and depending on how far they are from the threshold, these receivers' positions may totally lose the service or experience difficulties in their service. The relocation of the base stations after re-optimising the cost function using the new rms delay spread threshold (30 ns) increases the coverage yet to slightly lower values compared to that with the higher rms delay spread threshold. The new coverage values are 95.63%, 95.45% and 95.26% in

the closed environment, open environment and the environment with people respectively.

Moving to the low path loss threshold of 60 dB with the high rms delay spread threshold of 400 ns, the key point in the optimisation process becomes looking for wide areas with least objects to place the base stations. This will maximise the number of receivers' positions with low path loss that will mainly be around the base station. The opening of doors in some cases creates alternative areas with least objects and the base stations moves accordingly. The coverage percentages based on the optimal positions shown in Table 7.7 are 59.67%, 58.36%, 58.46% for the closed environment, open environment and environment with people respectively.

On the other hand, when the rms delay spread is lowered, some of the base stations move closer to objects that reduce the signal strength and hence reduce the rms delay spread values. The coverage obtained for the 60 dB and 30 ns thresholds is 58.63%, 55.82% and 57.13% for the closed environment, open environment and environment with people respectively. Note that the closed environment and environment with people have the same optimal positions coordinates but the coverage in the environment with people is lower as the presence of people attenuates the signal.

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	(7.175, 2.725) (2.675, 11.725) (5.675, 20.725)	(7.175, 2.725) (4.175, 10.225) (5.675, 20.725)	(7.175, 2.725) (2.675, 11.725) (5.675, 20.725)
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	(8.675, 7.225) (2.675, 16.225) (8.675, 20.725)	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)	(5.675, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)

Table 7.7: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.1 for different parameters' values (3 base stations)

7.4.2 The Optimal Base Stations' Locations Results Based on Equation 6.3

Similar to the one transmitter and two transmitters' scenarios, the same optimal positions are obtained when using equations 6.1 and 6.3 with the exception of 3 cases. Table 7.8 presents the results of the optimisation of equation 6.3 when three base stations are serving the environment with the ones different from these obtained when equation 6.1 is maximised underlined.

	Empty Environment	Closed Environment	Open Environment	Environment with People
$PL_{th}=90$ dB $DL_{th}=400$ ns	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	<u>(7.175, 2.725)</u> <u>(5.675, 8.725)</u> <u>(5.675, 20.725)</u>	(7.175, 2.725) (4.175, 10.225) (5.675, 20.725)	<u>(7.175, 2.725)</u> <u>(5.675, 7.225)</u> <u>(5.675, 19.225)</u>
$PL_{th}=60$ dB $DL_{th}=400$ ns	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)
$PL_{th}=60$ dB $DL_{th}=30$ ns	<u>(8.675, 4.225)</u> <u>(2.675, 16.225)</u> <u>(8.675, 20.725)</u>	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)	(5.675, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)

Table 7.8: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.3 for different parameters' values (3 base stations)

7.4.3 The Optimal Base Stations' Locations Results Based on Equation 6.5

The last cost function to be maximised in the chapter, when the environments are served by three base stations, is that of equation 6.5. Table 7.9 shows the optimal base stations coordinates for the various environment's configurations with different path loss and rms delay spread combinations. The same trends discussed for the single transmitter's scenario (section 7.2.3) are valid when the environments are served by three base stations.

		Empty Environment	Closed Environment	Open Environment	Environment with People
PL_{th}=90 dB DL_{th}=400 ns	$\alpha=0$	Any 3 positions	(1.175, 1.225) (1.175, 2.725) (1.325, 7.225)	(1.175, 1.225) (2.675, 1.225) (1.325, 7.225)	(1.175, 1.225) (2.675, 1.225) (1.325, 7.225)
	$\alpha=0.2$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
	$\alpha=0.7$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
	$\alpha=1$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
PL_{th}=90 dB DL_{th}=30 ns	$\alpha=0$	(11.675, 16.225) (11.675, 17.725) (13.175, 17.725)	(13.175, 19.225) (2.675, 20.725) (4.175, 22.225)	(2.675, 20.725) (10.175, 20.725) (10.175, 22.225)	(13.175, 19.225) (2.675, 20.725) (4.175, 22.225)
	$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	(8.675, 4.225) (5.675, 10.225) (5.675, 20.725)	(2.675, 4.225) (8.675, 4.225) (5.675, 17.725)	(5.675, 4.225) (5.675, 10.225) (5.675, 20.725)
	$\alpha=0.7$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	(7.175, 2.725) (5.675, 8.725) (5.675, 20.725)	(7.175, 2.725) (4.175, 10.225) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)
	$\alpha=1$	(7.175, 4.225) (5.675, 16.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 8.725) (5.675, 20.725)	(7.175, 2.725) (5.675, 7.225) (5.675, 19.225)	(5.675, 2.725) (7.175, 11.725) (5.675, 20.725)
PL_{th}=60 dB DL_{th}=400 ns	$\alpha=0$	Any 3 positions	(1.175, 1.225) (1.175, 2.725) (1.325, 7.225)	(1.175, 1.225) (2.675, 1.225) (1.325, 7.225)	(1.175, 1.225) (2.675, 1.225) (1.325, 7.225)
	$\alpha=0.2$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)
	$\alpha=0.7$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)
	$\alpha=1$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)
PL_{th}=60 dB DL_{th}=30 ns	$\alpha=0$	(11.675, 16.225) (11.675, 17.725) (13.175, 17.725)	(13.175, 19.225) (2.675, 20.725) (4.175, 22.225)	(2.675, 20.725) (10.175, 20.725) (10.175, 22.225)	(13.175, 19.225) (2.675, 20.725) (4.175, 22.225)
	$\alpha=0.2$	(8.675, 7.225) (11.675, 16.225) (11.675, 17.725)	(8.675, 4.225) (5.675, 10.225) (5.675, 17.725)	(5.675, 5.725) (4.175, 11.725) (5.675, 20.725)	(8.675, 4.225) (5.675, 10.225) (5.675, 17.725)
	$\alpha=0.7$	(8.675, 4.225) (2.675, 16.225) (8.675, 20.725)	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)	(5.675, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 4.225) (5.675, 10.225) (8.675, 19.225)
	$\alpha=1$	(5.675, 4.225) (7.175, 13.225) (5.675, 20.725)	(8.675, 7.225) (5.675, 10.225) (8.675, 19.225)	(7.175, 5.725) (4.175, 11.725) (8.675, 19.225)	(8.675, 7.225) (5.675, 10.225) (7.175, 17.725)

Table 7.9: Optimal base stations' positions in the empty, closed and open environments as well as the environment with people using the cost function of equation 6.5 for different parameters' values (3 base stations)

7.5 The Effect of The Cut-off Power Level on The optimal Transmitters' Positions

As previously discussed in section 5.8, the selection of the cut-off power level affected the optimal base stations positions, mainly when higher priority is given to the standard deviation (trade-off factor less than 0.5). In this section, the cost function of equation 6.1 will be maximised when the furnished environment is considered with all doors and most windows closed. Table 7.10 and Table 7.11 show the optimal base stations coordinates when one and two base stations are assumed to serve the environment for different path loss and rms delay spread thresholds. It can be noticed that the optimal results were not affected by the cut-off power level change with the exception of the case when the path loss and rms delay spread thresholds are set to 90 dB and 30 ns respectively with one transmitter serving the environment. As this cost function does not use the path loss and rms delay spread values directly in its definition and it only compares them to the thresholds, the cost function values are not affected. When lower cut-off power level is used, the rms delay spread values will be lower and the path loss values will be higher but compared to the thresholds selected, those changes were not able to highly modify the cost function values. However, when a single transmitter is serving the environment and the path loss and rms delay spread thresholds are set to 90 dB and 30 ns, the optimal transmitter obtained is equal to that obtained when the rms delay spread threshold is set to 400 ns (for the cut-off level of -60 dB). As lower cut-off power level results lower rms delay spread values, lowering the corresponding threshold to 30 ns did not affect the optimal position which is not the case when the -90 dB cut-off is used.

Cut-off Level	PL _{th} =90 dB DL _{th} =400 ns	PL _{th} =90 dB DL _{th} =30 ns	PL _{th} =60 dB DL _{th} =400 ns	PL _{th} =60 dB DL _{th} =30 ns
-60 dB	(7.175, 11.725)	(7.175, 11.725)	(7.175, 8.725)	(5.675, 10.225)
-90 dB	(7.175, 11.725)	(5.675, 8.725)	(7.175, 8.725)	(5.675, 10.225)

Table 7.10: Optimal base station's coordinates in the closed environment for cut-off power levels of -60 dB and -90 dB for different path loss and rms delay spread thresholds

Cut-off Level	PL _{th} =90 dB DL _{th} =400 ns	PL _{th} =90 dB DL _{th} =30 ns	PL _{th} =60 dB DL _{th} =400 ns	PL _{th} =60 dB DL _{th} =30 ns
60 dB	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(8.675, 7.225) (7.175, 17.725)	(5.675, 10.225) (8.675, 19.225)
90 dB	(5.675, 5.725) (5.675, 19.225)	(5.675, 5.725) (5.675, 19.225)	(8.675, 7.225) (7.175, 17.725)	(5.675, 10.225) (8.675, 19.225)

Table 7.11: Optimal base station's coordinates in the closed environment for cut-off power levels of -60 dB and -90 dB for different path loss and rms delay spread thresholds (2 base stations)

7.6 The Effect of Antenna Polarisation on The Cost Function Values

Section 5.9 discussed the effect of polarisation change on the cost functions defined in chapter 5. In this section, the cost function of equation 6.1 will be calculated when the base station is located at each of the fourteen locations specified in Figure 5.21 when the environment is considered with open doors and windows. Different path loss and rms delay spread thresholds are considered and the cost function values are shown in Figure 7.13. When the path loss threshold is set to 90 dB with either rms delay spread values (400 ns or 30 ns), the perpendicular polarisation results higher cost function values hence higher coverage as the perpendicular polarisation increases the field strength values. This will be discussed further in chapter 8. Note that the values of the cost function for both polarisation varies in the same manner. On the other hand, when the path loss threshold is lowered to 60 dB with 400 ns rms delay spread threshold, the parallel polarisation gives higher cost function values (higher coverage) but both curves still vary based on the same trends. Consequently, for those scenarios, the optimal base stations coordinates are not supposed to vary. As for the case when both the path loss and rms delay spread thresholds are low (60 dB and 30 ns respectively), the cost function values are not varying based on the same trends thus the optimal base stations coordinates may be affected in this case.

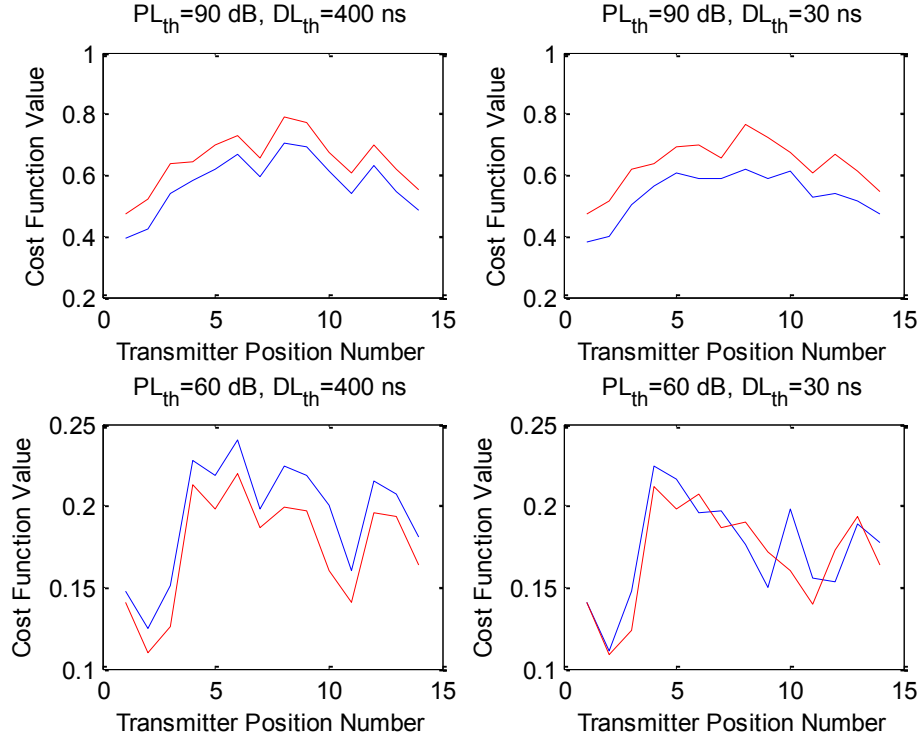


Figure 7.13: Cost function values for 14 transmitter locations for the open environment for different path loss and rms delay spread thresholds with the blue and red colours corresponding to the parallel and perpendicular polarisations respectively

7.7 Conclusions

It was shown in this chapter that the optimal base stations' locations are sensitive to environment changes. After the environment is filled with objects, the signal cannot travel far in the environment. It is however blocked by the objects, attenuated (depending on the material type) before being reflected back. This will increase the overall path loss over the environment and decrease the coverage percentage. A single transmitter cannot handle the furnished environment even for high receiver's sensitivity and low symbol rate. However, the good effect of the presence of furniture in the environment is sometimes lower rms delay spread values compared to an empty environment, mainly when the materials highly attenuate the signal in a way that decreases the number of reflections. Note that for low speed systems, the time parameter does not highly affect the optimal position although this is dependent on the form and constituent of the environment. In other words, the maximum data rate below which the time parameter can be ignored is environment dependent. In a narrow

environment for example, the rms delay spread values are expected to be higher as seen in case of the environment's corridor.

In addition, the changes applied to the furnished environment represented by opening the windows and doors or the addition of people generally affect the optimal base stations' locations. The base stations may or may not relocate after the environment change depending on how much the field strength and rms delay spread distributions have changed with respect to the corresponding threshold values.

On the other hand, any indoor environment is subject to continuous changes similar to those modelled in this chapter. These changes affect the service and may require a change in the optimal base stations' positions which is not generally practical. Furthermore, in case the optimal base stations' positions are not affected by the environment change, active receivers may lose the service, thus some solutions are suggested in chapter 8 in order to reduce the effect of environment changes on the service.

Chapter 8: Reacting to The Dynamically Changing Environment

8.1 Introduction

In chapters 5, 6 and 7, the same indoor environment was considered in different circumstances. The environment was first considered empty with only walls, doors and windows modelled. Furniture is then added to the environment. The two other environment configurations represent a modification of the furnished environment scenario where doors and windows are opened or people are distributed throughout the environment. It was shown that the addition of furniture to the environment highly affects the channel characteristics and changes the optimal base stations' positions. In addition, the optimal base stations' positions are also sensitive to changes such as the opening of doors and windows or the presence of people in the environment.

Similar changes happen frequently in any indoor environment. It is impossible that every time a change occurs to the environment the optimisation process is repeated and the base stations are relocated. On the other hand, due to environment changes, active receivers may lose the service. Thus some intelligence must be added to the base stations so that they can detect changes occurring in the environment mainly by monitoring the receivers' power and then act accordingly.

In this chapter, three actions the base station can perform to respond to environment changes are proposed. The first proposed response to environment changes is increasing the amount of power the base station emits gradually until the active receiver regains service if possible. An alternative can be a change in the polarisation. As shown in chapter 4, when the antenna polarisation changes, the channel characteristics change and it may be possible that a receiver's location that lost the service due to changes in the environment regains it after the polarisation modification. The last proposed approach is the movement of the base station horizontally or vertically in the plan view for a limited distance. Note that this proposition requires change of the standard base station where a control system needs to be added to decide the movement direction and distance and gives the order to the mini-car robot, for example, responsible of moving the base station.

8.2 Emitted Power Change

The first technique proposed in this chapter to overcome the effect of environment changes allows the base station to increase its power gradually until the receiver regains service. Assume that a receiver is transferring data and suddenly changes take place in the environment and the receiver loses the connection. In this case, the base station starts increasing its power gradually until the service is back at the receiver end. The amount of the power increase depends on how much the path loss has increased above the receiver's sensitivity. It may be possible that the base station reaches its maximum power and the receiver is not able to regain the service. Note that as the amount of emitted power is increased, the interference with adjacent base stations increases.

In order to illustrate this, a single base station is located at its optimal position with coordinates of (5.675, 8.725) obtained after the minimisation of the cost function of equation 5.1 with a trade-off factor of 0.7 in the empty environment (refer to chapter 5). The minimal amount of power required to cover 80% of the environment was found to be 18.05 dBm when the receiver's sensitivity is set to -65 dBm. This means that a receiver's position with path loss higher than 83.05 dB will not be served. As previously discussed, the base stations' locations will be selected in the design stage thus the selection will be based on an empty environment and then it may be impossible to relocate them. The closed and open environments as well as the environment with people are assumed to be served then by the base station located at (5.675, 8.725). The channel characteristics will be different for each environment's configuration and the distribution of the served receivers' locations will change accordingly. Figure 8.1 shows the receivers' locations having their path loss lower than 83.05 dB in cyan for the four environment's configurations. The first thing to mention is that once furniture is added to the environment, the coverage has dropped significantly. A receiver's position is selected from the area circled in yellow in Figure 8.1. This location has a path loss of 54.5 dB in the empty environment, 70.26 dB in the closed environment, 94.37 dB in the open environment and 70.21 dB in the environment with people. Consequently, the receiver loses the service only when doors and windows are opened in the environment and will not regain service until the base station increases its power from 18.05 dBm to 29.37 dBm. Another receiver's position is selected from the area circled in black. The selected position loses service when doors and windows are opened as well as when

people are added to the environment. The corresponding path loss values are 98.68 dB and 108.08 dB respectively while it was 67.49 dB in the closed environment. The amount of power increase is higher than that of the previous selected receiver's position. Note that a receiver located at a position that is not initially covered by the base station may never be served as the base station cannot be aware of its presence.

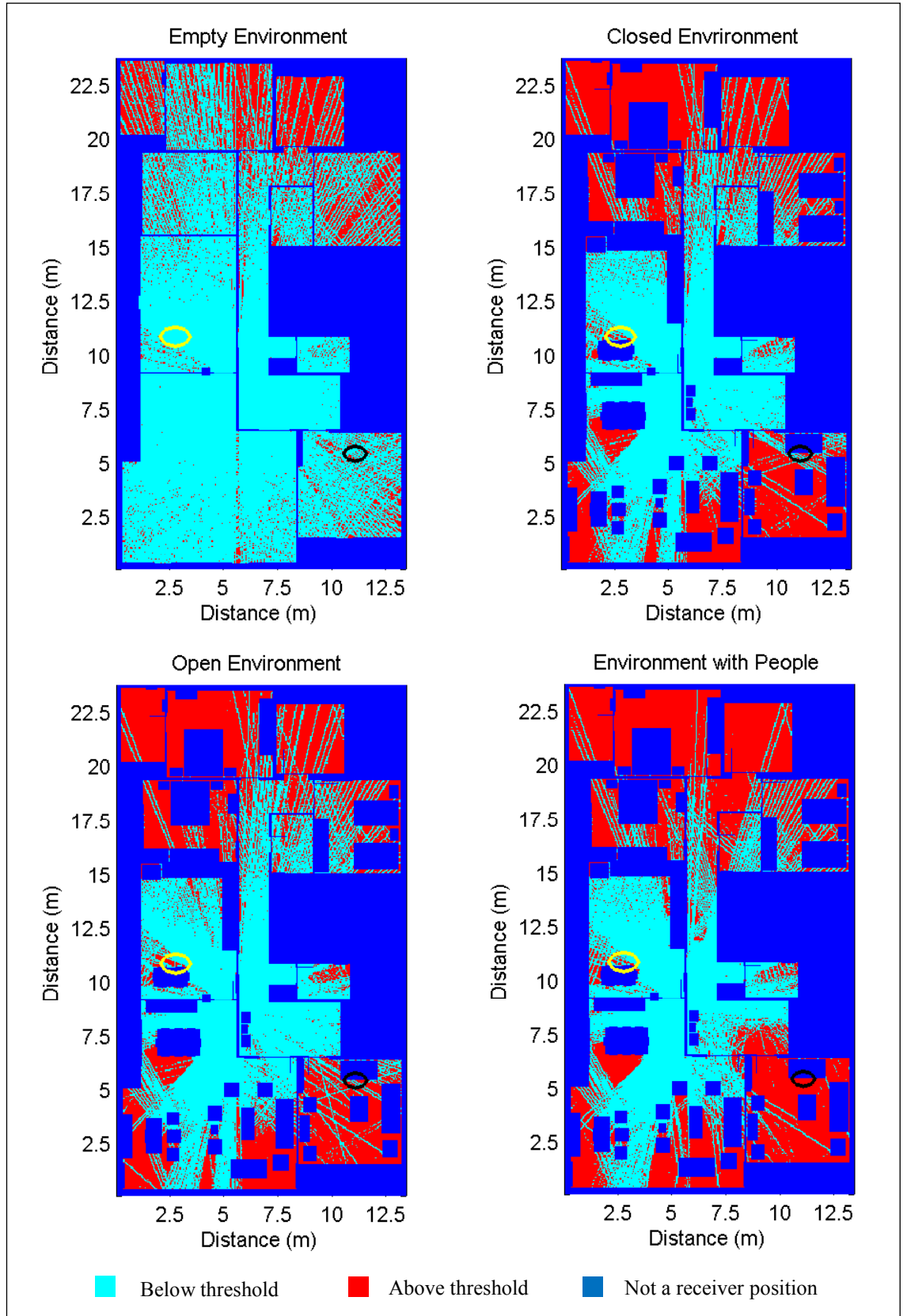


Figure 8.1: Receivers' positions having their path loss below 83.05 dB in the empty, closed and open environments as well as the environment with people for a transmitter's position coordinates of (5.675, 8.725)

The same concept applies when the base station is positioned based on any selection of cost function's parameters. Similarly, when multiple base stations are serving the environment, if a receiver misses the service, the base station to which the receiver is connected increases its power until the service is back again unless the amount of power required is beyond the maximum power limit of the base station. However, in the case of multiple base stations there is a possibility that another base station handles the receiver after the environment change instead of increasing the power of the first one. Note that the emitted power can be decreased as the power of the receiver increases or when the receiver terminates the data transfer.

On the other hand, the power increase is not applied when the cost functions defined based on the path loss and rms delay spread values are used (refer to chapter 6). The rms delay spread values are supposed to change when the emitted power is varied but the emitted power of the ray tracing software cannot be changed.

8.3 Antenna Polarisation Change

Increasing the amount of emitted power to overcome the effect of environment changes is not always effective. The more the path loss at the receiver end increases due to the environment change, higher power increase is required which may exceed the maximum amount the base station can emit. An alternative technique is to change the antenna polarisation from parallel to perpendicular or vice versa. It was shown in chapter 4 that when the antenna polarisation is modified different channel characteristics are obtained hence, a receiver that has lost the service due to environment changes may resume the data transfer after a polarisation change.

The same scenario discussed in section 8.2 is considered or in other words, the base station is located at (5.675, 8.725) with 83.05 dB path loss threshold value below which a receiver position is considered to be served. Figure 8.1 shows the covered locations for the different environment's configurations when parallel antenna polarisation is used. It can be seen that due to environment changes some receivers' locations lost the service. As an example, after the addition of people to the closed environment, 10.33% of the receivers' location lost the service. However, after the antenna polarisation is changed to perpendicular in the environment with people,

50.53% of these locations got the service back which represents 5.22% of the total receivers' locations. Figure 8.2 shows in red the receivers' locations that lost the service after the environment change and the ones that regained the service after the modification of the polarisation. Comparing the coverage when either the parallel or perpendicular polarisations are used in the environment with people, 4% and 13.12% (including the 5.22% that regained the service) of the receivers' locations are served only when the parallel and perpendicular polarisation are used respectively. The rest of the receivers' locations have the same status (covered or uncovered) when either of the two polarisations is used.

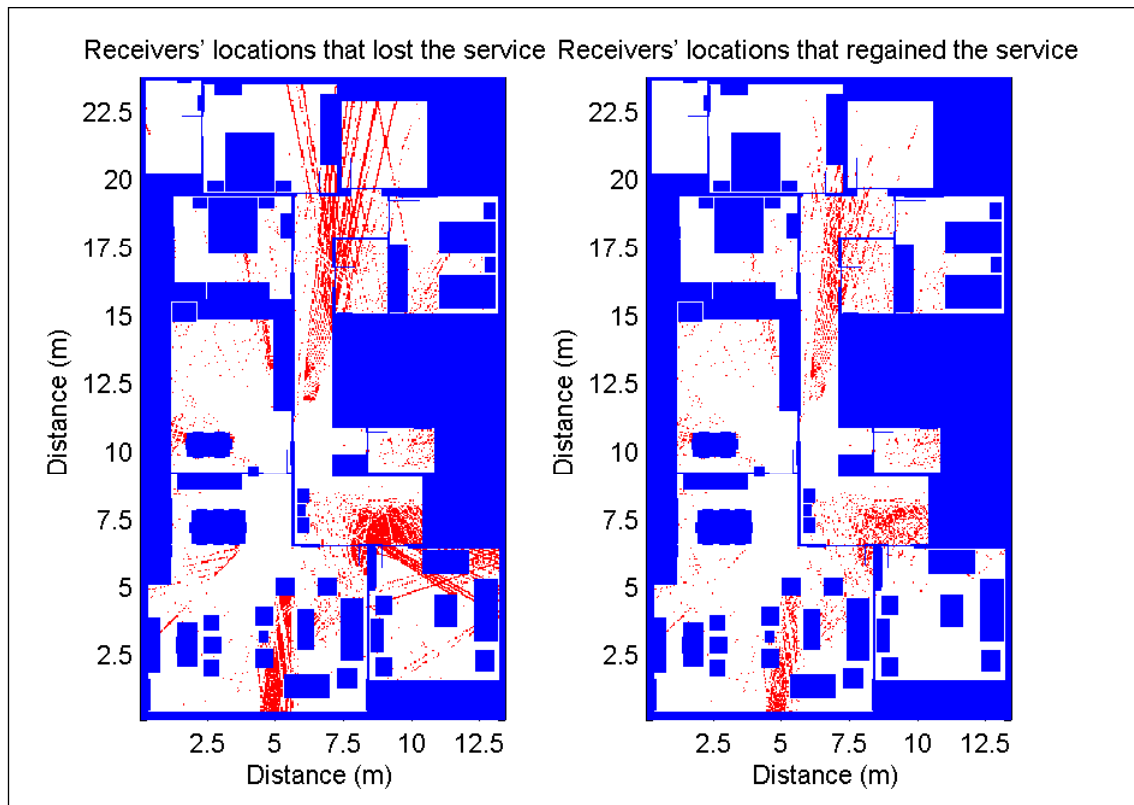


Figure 8.2: Receivers' locations that lost the service after the addition of people to the closed environment and these that got back the service after changing the antenna polarisation of the base station at (5.675, 8.725) to perpendicular

Furthermore, the same concept can be applied when multiple base stations are serving the environment. Whenever a receiver's location loses the service as a result of environment changes, the base station serving the receiver alters its antenna polarisation as long as none of the other base stations is able to handle the service. As an example,

assume that two base stations are located at (5.675, 5.725) and (5.675, 19.225) which are the optimal positions obtained as a result of the optimisation of equation 5.1 based on the empty environment with the trade-off factor set to 0.7. The minimal amount of power required to cover 80% of the possible receivers' locations was found to be -0.28 dBm, thus, based on -65 dBm receiver's sensitivity, the critical path loss value above which a receiver's location is not served is 64.72 dB. Keeping the base stations at the mentioned locations with the same emitted power and adding furniture to the environment (closed environment) decreases the coverage to 49.62%. After introducing changes to the environment (open environment and environment with people), some of the receivers' locations lose the service. Changing the antenna polarisation of the base stations to perpendicular did not add much to the service. If the polarisation of the base station located at (5.675, 19.225) is changed to perpendicular in the environment with people, 1.7% of the receivers' locations that were not served when the parallel polarisation was used are covered while 4.32% of the receivers' positions served with the parallel polarisation are not served with the perpendicular polarisation. In other words, the parallel polarisation covers an extra 2.62% compared to the perpendicular polarisation. In addition, some of the 1.7% of the receivers' locations are not already covered before the environment change. Figure 8.3 shows in cyan the covered receivers' positions in the closed environment as well as the environment with people when the base stations are at (5.675, 5.725) and (5.675, 19.225). It can be seen that some of the receivers' locations (2.76%) lost the service. The area circled in black in Figure 8.3 is one of the areas affected. This area is served by the base station at (5.675, 19.225). After changing the polarisation of this base station to perpendicular, different locations are covered. Comparing the coverage of both polarisations, the receivers' positions that are covered only after using the perpendicular polarisation are shown in red in Figure 8.4. Looking into the same area highlighted in Figure 8.3, it can be seen that some of the receivers' positions that lost the coverage after the environment change are able to regain it after modifying the polarisation (4.19% of those that lost the service). Furthermore, changing the polarisation of the base station at (5.675, 5.725) is not effective too where most of positions covered after the polarisation change were not initially covered before the environment change. The polarisation change does not seem to be effective for this scenario due to the low path loss threshold value obtained as the minimal amount of power was selected based on the empty environment which lowers the power requirement added to the fact that using multiple base stations lowers the

power too. Recall from chapter 4 that the reflection coefficient of the parallel polarisation is always lower than that of the perpendicular polarisation. This means that whenever any reflection occurs after the signal hits a wall at the boundary of the environment, a bigger portion of the signal goes outside the environment if the parallel polarisation is used as opposed to the perpendicular polarisation. For this reason, with the perpendicular polarisation, higher signal level can reach farther locations. When the path loss threshold is low, the receivers' locations satisfying the coverage criterion will mostly be close to the base stations where both polarisations will have low but different path loss values. Consequently, the improvement of the perpendicular polarisation will be limited. To clearly visualise this, the cumulative probability distribution function of the path loss values through the environment with people when the base station is located at (5.675, 5.725) is plotted in Figure 8.5 for both the parallel and perpendicular polarisations. The two functions are almost equal for path loss values less than 55 dB, and then a tiny difference is seen until the path loss values of 80 dB. After the 80 dB path loss value, the difference between the two curves becomes larger. Thus, for higher path loss threshold values, higher difference between the coverage of the two polarisations is achieved and the polarisation change becomes more effective to overcome the effects of environment changes.

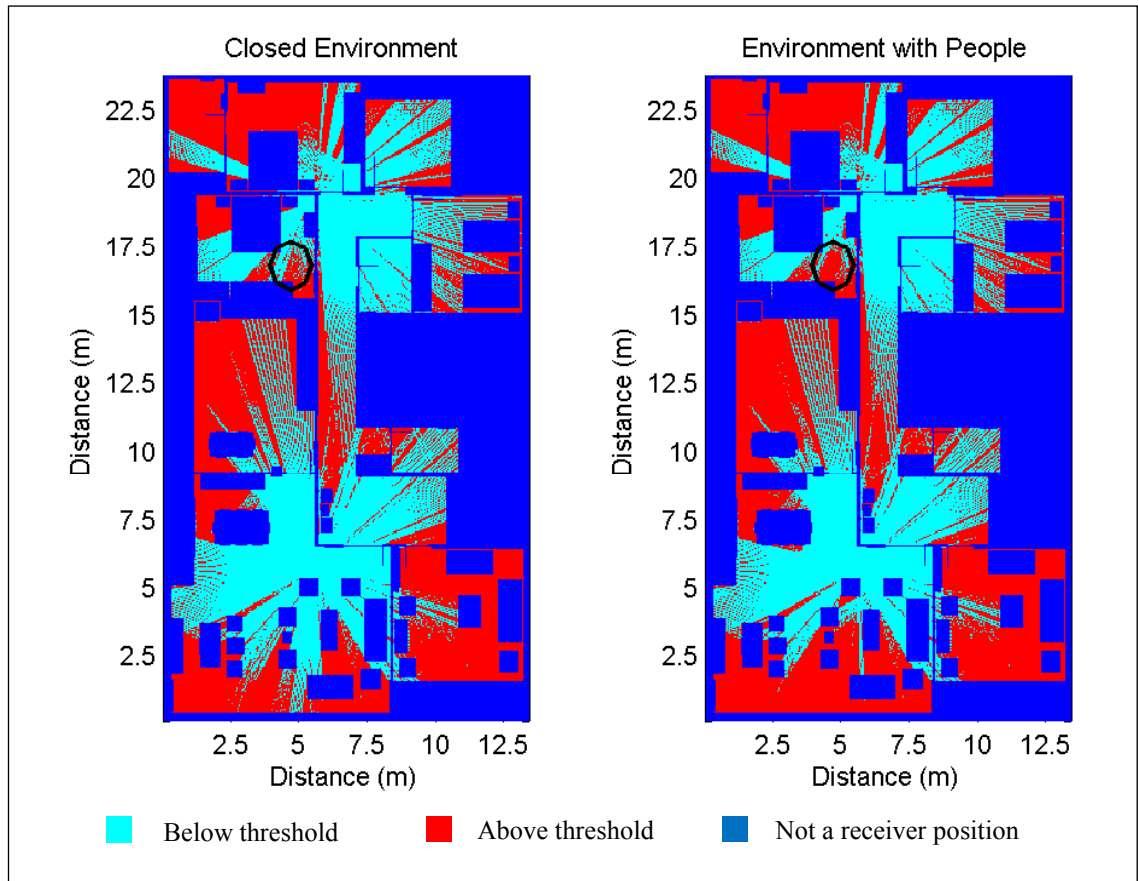


Figure 8.3: Receivers' positions having their path loss below 64.72 dB in the closed environment and the environment with people for two transmitters with coordinates of (5.675, 5.725) and (5.675, 19.225)

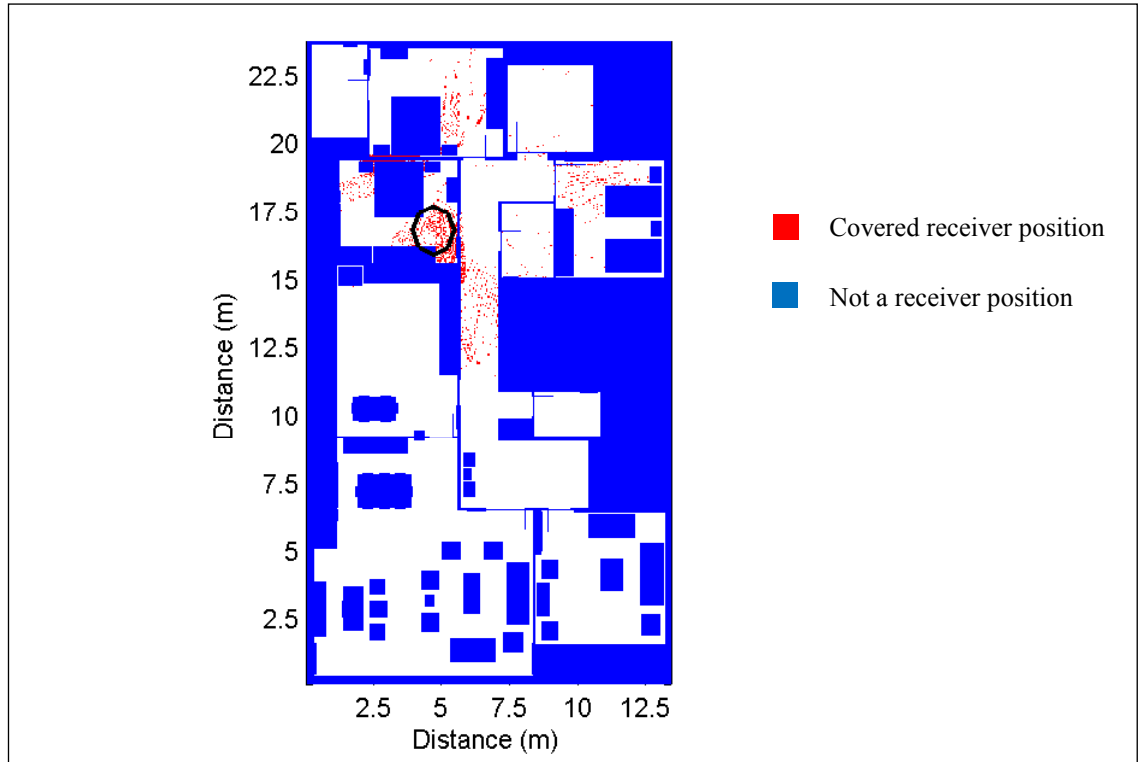


Figure 8.4: Receivers' positions covered only when the base station at (5.675, 19.225) uses perpendicular polarisations while that at (5.675, 5.725) uses parallel polarisation in the environment with people

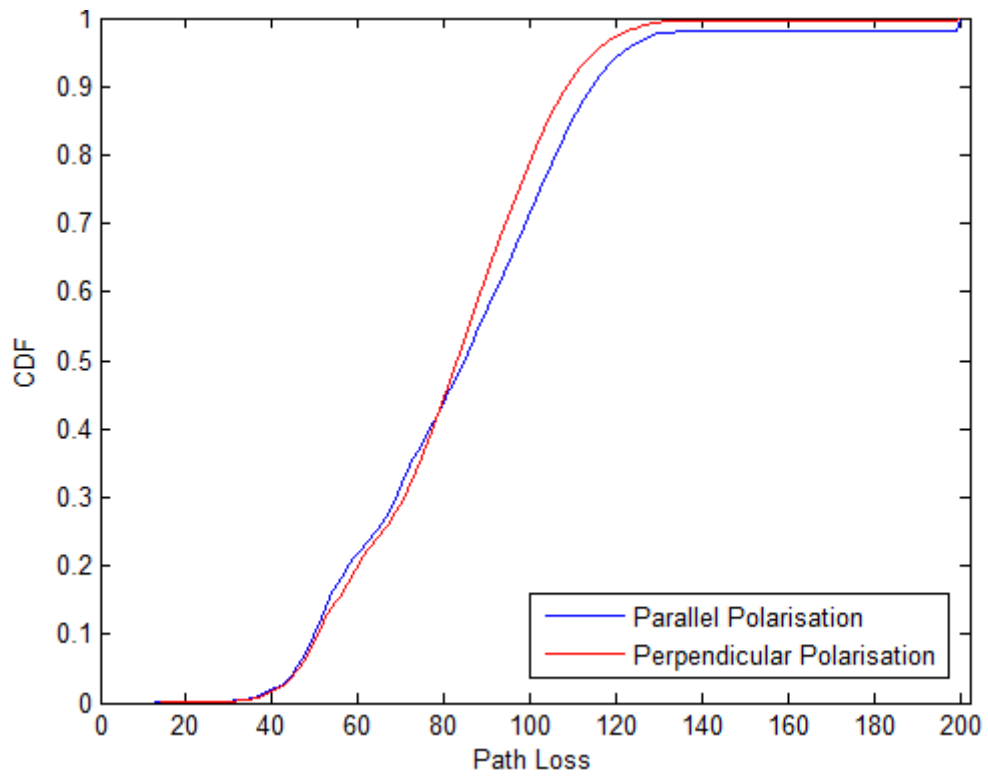


Figure 8.5: Cumulative probability distribution function of the path loss values throughout the environment with people when the base station at (5.675, 5.725) uses either the parallel or perpendicular polarisations

On the other hand, the minimisation of equation 5.1 in the closed environment instead of the empty environment leads to the same optimal positions just discussed though for a different trade-off factor value (0.2). As the environment is furnished, the minimal power requirement to cover 80% of the receivers' positions is higher. It is 15.33 dBm thus the path loss threshold becomes 80.33 dB. The same environment change is considered, that is people are added to the environment. Figure 8.6 shows the coverage for both the closed environment and the environment with people. 3.41% of the possible receivers' locations missed the service after the environment change. These locations are shown in Figure 8.7. If the polarisation of the base station at (5.675, 5.725) is switched to perpendicular, 43.69% of these receivers locations (1.49% of the total receivers' locations) regain the service whereas if that of the base station at (5.675, 19.225) is changed, 14.07% of these receivers' locations gets the service back (0.48% of the total receivers' locations). Figure 8.8 indicates the receivers' locations that got the service back after the change of the polarisation of each base station separately. The change of the polarisation of the base station at (5.675, 5.725) is more effective as the area that is highly affected is initially covered by this base station. Note that few receivers' locations can regain the service when any of the two base stations changes its polarisation as they are at the edge of the coverage area of each base station.

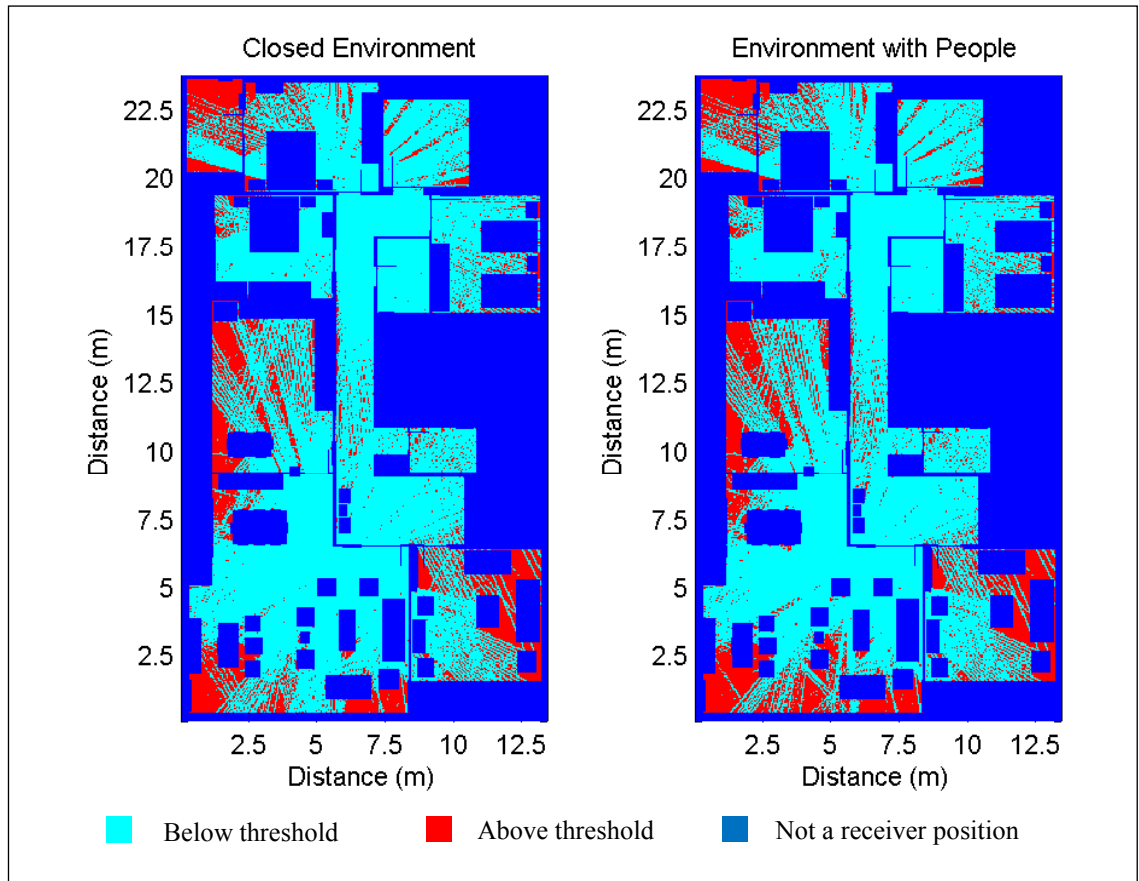


Figure 8.6: Receivers' positions having their path loss below 80.33 dB in the closed environment and the environment with people for two transmitters with coordinates of (5.675, 5.725) and (5.675, 19.225)

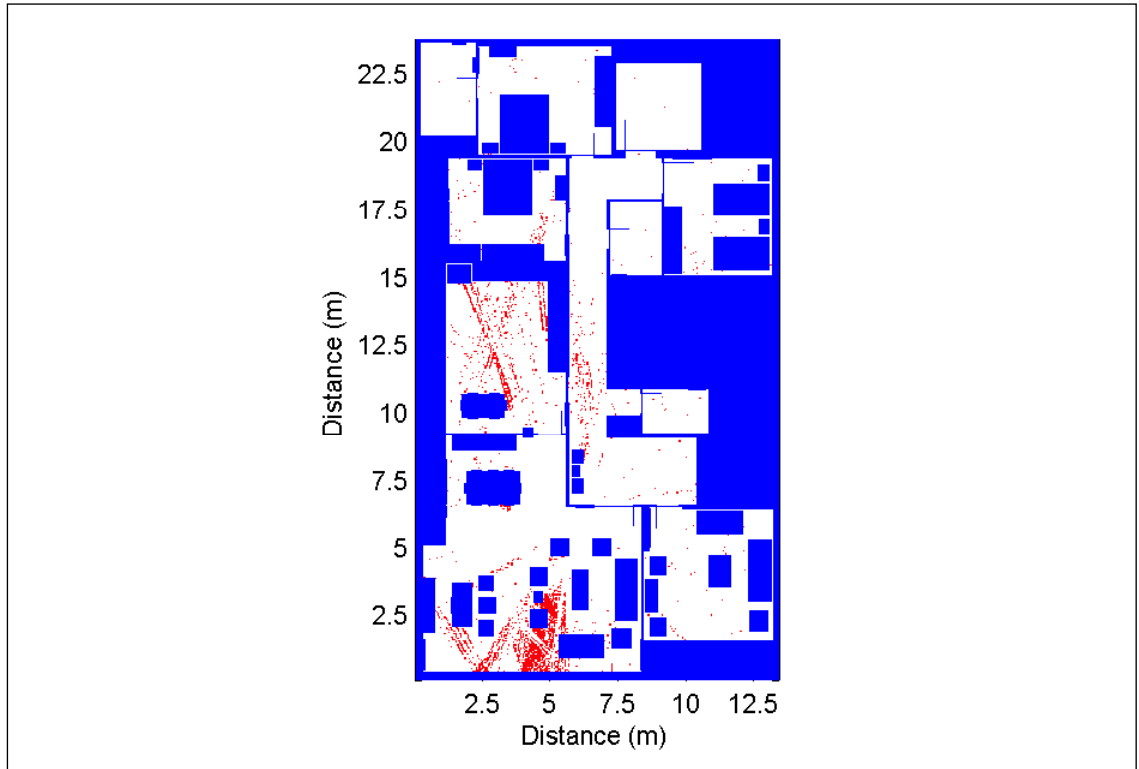


Figure 8.7: Receivers' locations that lost the service after the addition of people to the closed environment for two transmitters with coordinates of (5.675, 5.725) and (5.675, 19.225)

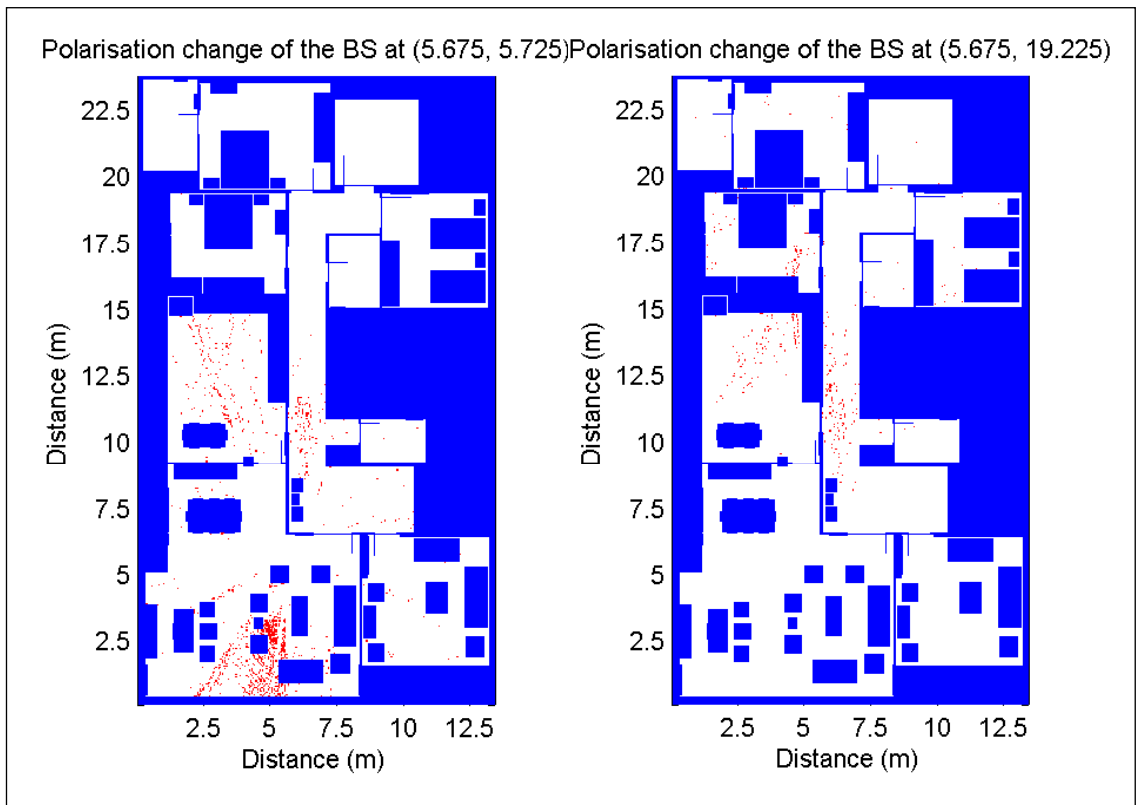


Figure 8.8: Receivers' locations that got the service back after changing the antenna polarisation of the base stations at either (5.675, 5.725) or (5.675, 19.225) to perpendicular

In addition, the optimal base stations' locations were found using cost functions that use both the path loss and the rms delay spread values (refer to chapters 6 and 7). A receiver's location is assumed to be served when both parameters are below predefined threshold values. After any environment change, some receivers' locations lose the service. Changing the polarisation is also suggested in this case. In order to check how useful this technique is, the base stations are located in the various furnished environment's configurations based on the optimal positions obtained after maximising the cost functions defined in chapter 6 when the channel characteristics of the empty environment are used. The antenna polarisation is then modified to perpendicular and the coverage is compared for the different environment's scenarios. The first common thing for the different optimal positions considered is that the perpendicular polarisation lowers the rms delay spread values throughout the environment and consequently the main controlling parameter of the covered receivers' locations is the path loss. This leads to conclusions similar to these previously discussed when the coverage is defined according to the path loss values alone with the difference that the percentage of receivers' positions covered only when the perpendicular polarisation is used becomes higher especially as some of the locations where the rms delay spread is lowered might have their path loss below the path loss threshold.

As an example, a single base station is located at (4.175, 10.225) which is the optimal location obtained after the maximisation of equation 6.1 with the path loss and the rms delay spread thresholds set to 90 dB and 400 ns respectively using the empty environment channel characteristics. The base station located at (4.175, 10.225) is then assumed to serve the closed environment and the environment with people. Comparing the covered locations in both environments, 4.88% of the receivers' locations lost the service due to the addition of people to the environment. Whereas, if the antenna polarisation is changed to perpendicular in the environment with people, 55.94% of the receivers' locations that lost the coverage due to the environment change can enjoy the service again. This represents 2.73% of the possible receivers' locations. Figure 8.9 shows in red the distribution of the receivers' positions that missed the service after the addition of people to the environment as well as these that got back the service after the polarisation change.

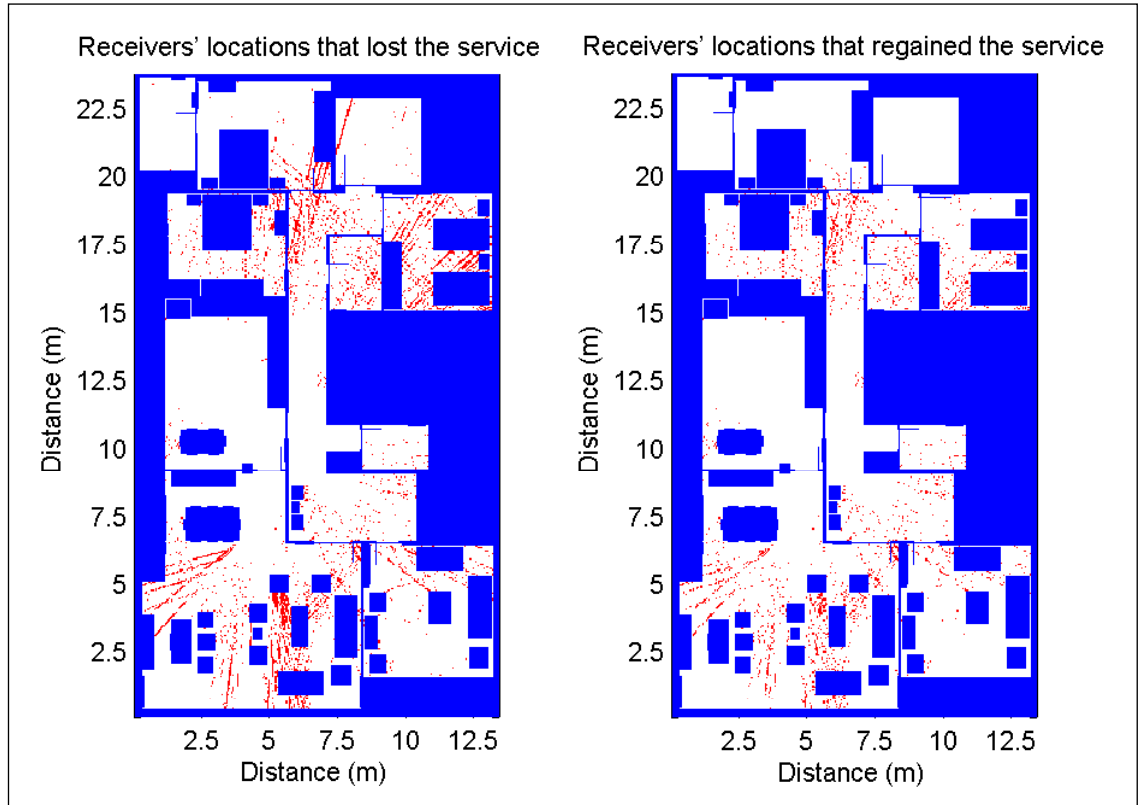


Figure 8.9: Receivers' locations that lost the service after the addition of people to the closed environment and these that got back the service after changing the antenna polarisation of the base station at (4.175, 10.225) to perpendicular

Furthermore, assume that the base station is located at (8.675, 7.225), which represents the optimal position obtained once the cost function of equation 6.1 is maximised in the empty environment with path loss and rms delay spread thresholds set to 90 dB and 30 ns respectively. If the closed environment is served with the base station being at this latter position, 8.58% of the receivers' positions lose the service once the door and windows are open (open environment). If the polarisation of the base station serving the open environment is switched to perpendicular, 67% of the receivers' positions that missed the service enjoy the service back again which is equivalent to 5.76% of all the possible receivers' locations (Figure 8.10).

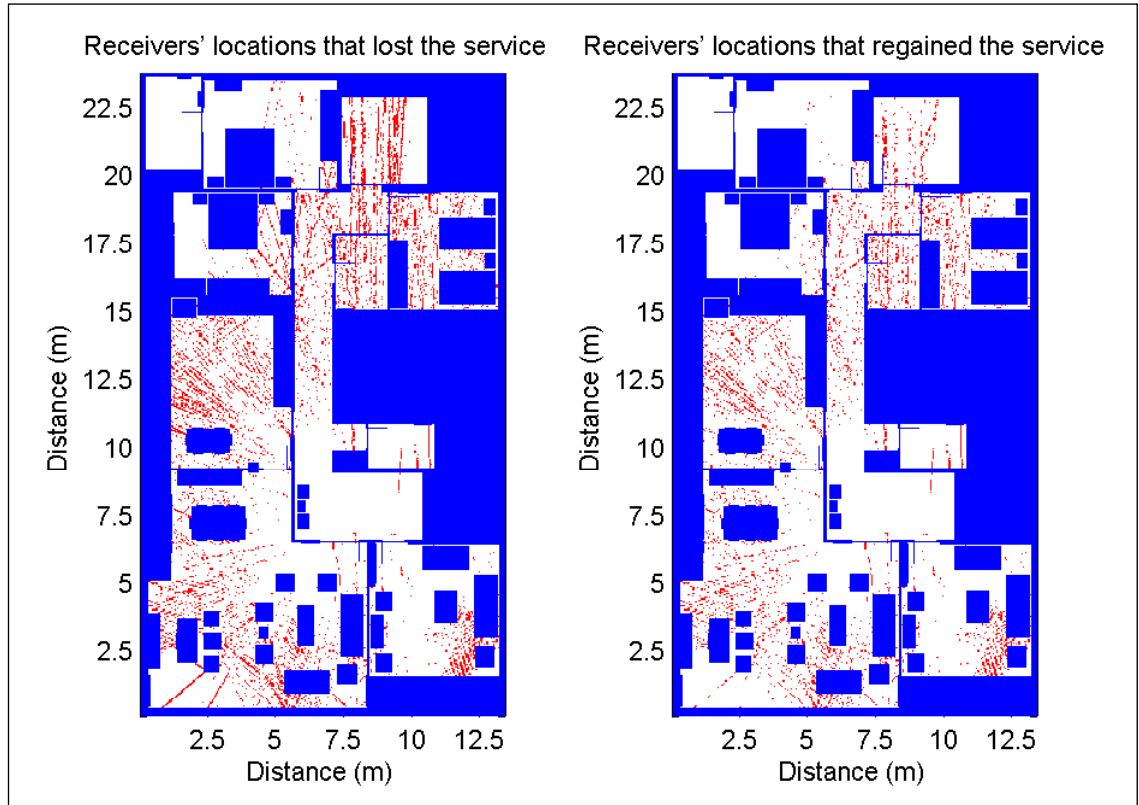


Figure 8.10: Receivers' locations that lost the service after opening the doors and windows of the closed environment and these that got back the service after changing the antenna polarisation of the base station at (8.675, 7.225) to perpendicular

On the other hand, as the path loss threshold value is decreased, the polarisation change does not give much improvement. The whole coverage highly deteriorates in the initial environment and the number of receivers' locations that lose the service after the environment change is lowered. Recall that the same optimal position with coordinates (8.675, 7.225) is obtained after the optimisation of equation 6.1 within the empty environment with 60 dB or 90 dB path loss threshold and 30 ns rms delay spread threshold. While keeping the base station at this location within the closed environment then opening the doors and windows, 5.24% of the receivers' locations lose the service and only 9.2% of these locations get the service back. The low efficiency of the polarisation change is due to the low path loss threshold as discussed earlier in this chapter.

As the number of base stations serving the environment increases, the service improves throughout the environment. If the path loss threshold is high, the percentage of receivers' locations that loses the service after the environment change decreases.

However, if lower path loss threshold is used, this percentage increases again but the polarisation change efficiency gets lower as the difference between the coverage of the parallel and perpendicular polarisations becomes limited.

8.4 Base Station Movement

The last technique proposed in this chapter to overcome the effect of environment changes is to move the base station vertically northward or southward or alternatively in the horizontal direction westward or eastward as long as there are no obstacles in the desired direction of movement. The suggested distance is up to one metre in each direction. Note that larger distance may not be practical. This can be applied by having a wired base station or by placing the base station on a mini-car robot. In order to test how effective is this technique, the base stations are positioned at their optimal positions and then moved by a step of 20 centimetres to a maximum of one metre in four directions. If there are obstacles within the path the base station is following, the maximum move will be limited to the maximum attainable point before the one metre distance is reached.

With the aim of examining the performance of this technique, a single base station is located in the closed environment at the optimal position (7.175, 11.725) obtained after the minimisation of equation 5.1 using the empty environment path loss values for a trade-off factor of 0.2. Based on the minimal power requirement that provides 80% coverage within the empty environment, the path loss threshold is 83.53 dB. After opening the doors and the windows of the closed environment, 5.78% of the receivers' locations lost the service. Depending on the obstacles surrounding this base station, it can move up to 1 metre northward, southward or westward. The highest improvement is achieved while moving northward. When the base station moves 20 centimetres northward, 51.75% of the receivers' locations that lost the service regain it. While continuing the movement northward with a step of 20 centimetres until the maximum movement of 1 metre is reached, 57.01%, 57.24%, 55.65% and 55.27% of them regain the service respectively. The worst improvement achieved is 48.54% and it corresponds to a 60 centimetres southward movement. After each movement, the distribution of the recovered receivers' location is different. Figure 8.11 shows the

distribution of the receivers' positions that lost the service after the environment change as well as the recovered locations after moving the base station northward.

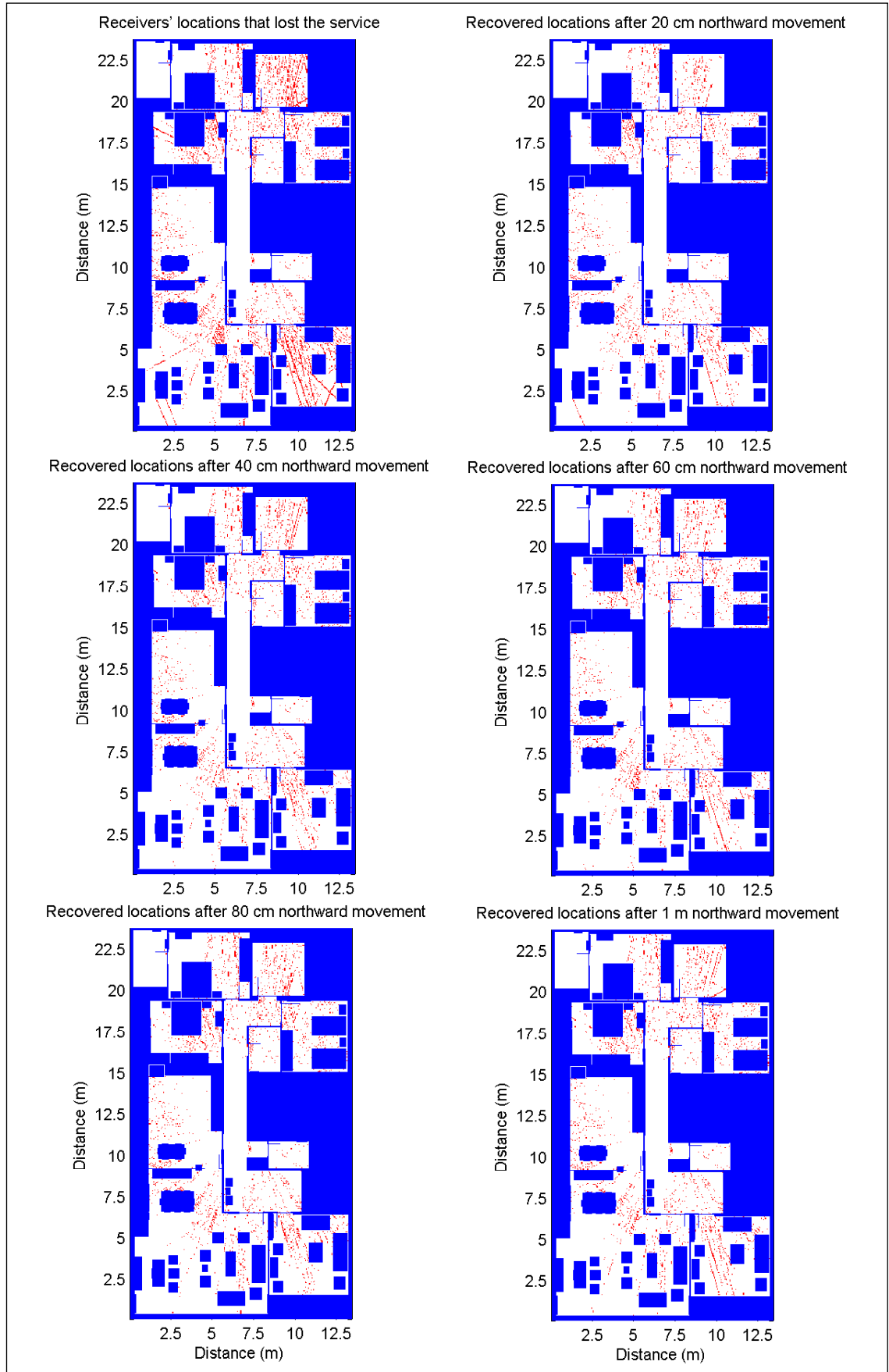


Figure 8.11: Receivers' locations that lost the service after opening the doors and windows of the closed environment and those that got back the service after moving the base station located at (7.175, 11.725) 1 metre northward with a step of 20 centimetres

As another example, if the trade-off factor is changed to 0.7, the optimal location moves to (5.675, 8.725) and the minimal power becomes 83.05 dB. Using this base station's settings in the closed environment then adding people to the environment deteriorates the service of 10.33% of the receivers' locations. For this base station's location, the possible movements are up to 40 centimetres northward and up to 1 metre southward or westward. Moving westward by a step of 20 centimetres up to 1 metre gives the service back to 24.34%, 30.14%, 37.11%, 38.85% and 39.89% of the receivers' locations that lost the service due to the environment change. In this case, the improvement looks to increase with the movement distance as the base station is moving farther from a person located close to the original base station's location. The distribution of the receivers' locations that lost the service as well as those that regained the service is shown in Figure 8.12 for the different westward movement distances. Note that the highest improvement achieved through all the possible movements is 45.14% and it corresponds to the 40 centimetres northward movement. It is expected that the northward movement increases the improvement further as the base station will be distant from the person but due to an obstacle, the base station cannot move further.

On the other hand, the base station's movement in any direction affects the other possible receivers' locations that were not initially affected by the environment change. Some locations will lose the service while others will be served in a balanced manner. This can be seen by observing the cumulative probability distribution functions of the path loss values throughout the possible receivers' locations for the different movements. In the open environment, the cumulative distribution functions for the various movement distances are almost the same. As for the environment with people, a slight difference is visible unless the base station is getting very close to a person's location where the overall coverage may deteriorate. Figure 8.13 shows the distribution functions when the base station at (7.175, 11.725) is not moved as well as if it moves northward in the open environment. Furthermore, Figure 8.14 shows the cumulative distribution functions in the environment with people when the base station is at (5.675, 8.725) and when it moves up to 1 metre westward.

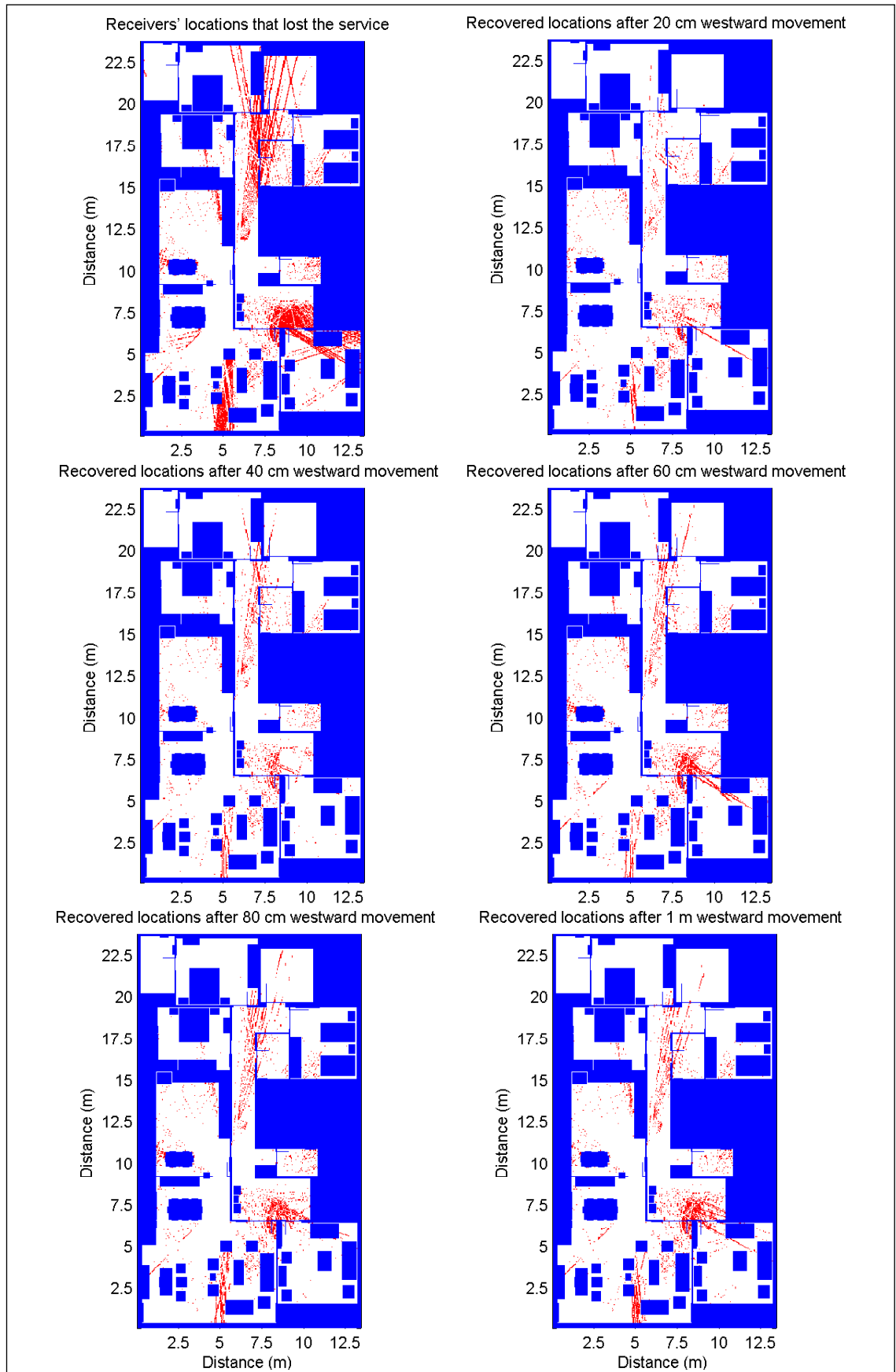


Figure 8.12: Receivers' locations that lost the service after adding people to the closed environment and those that got back the service after moving the base station located at (5.675, 8.725) 1 metre westward with a step of 20 centimetres

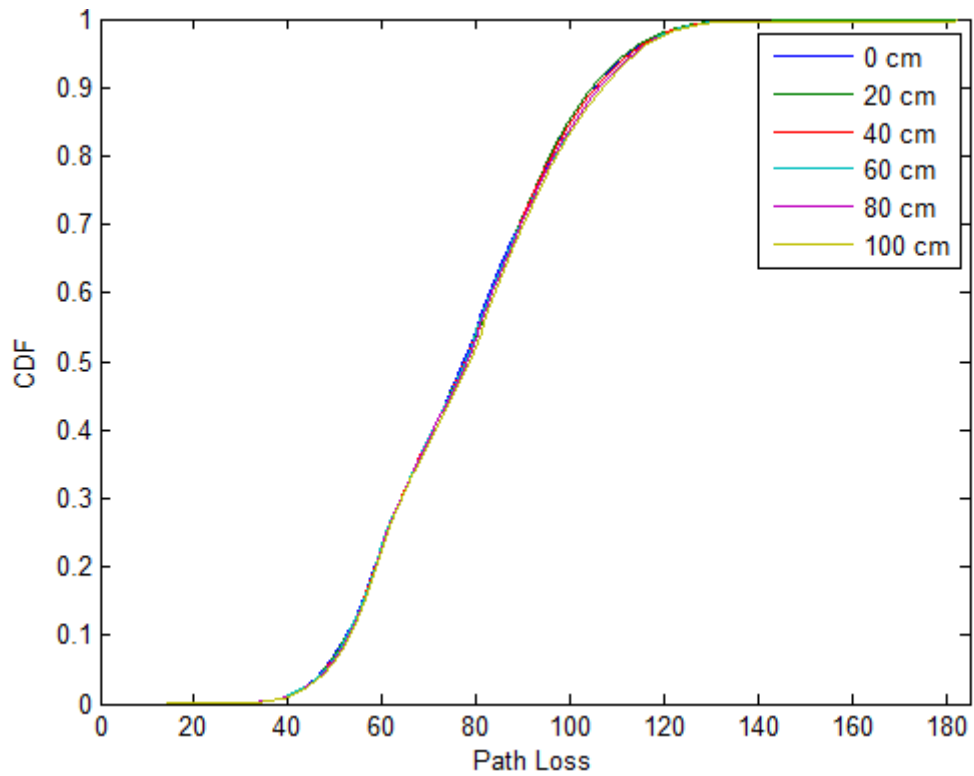


Figure 8.13: Cumulative probability distribution functions of the path loss values throughout the open environment when the base station is at (7.175, 11.725) and when it moves northward to a maximum of 1 metre with a step of 20 centimetres

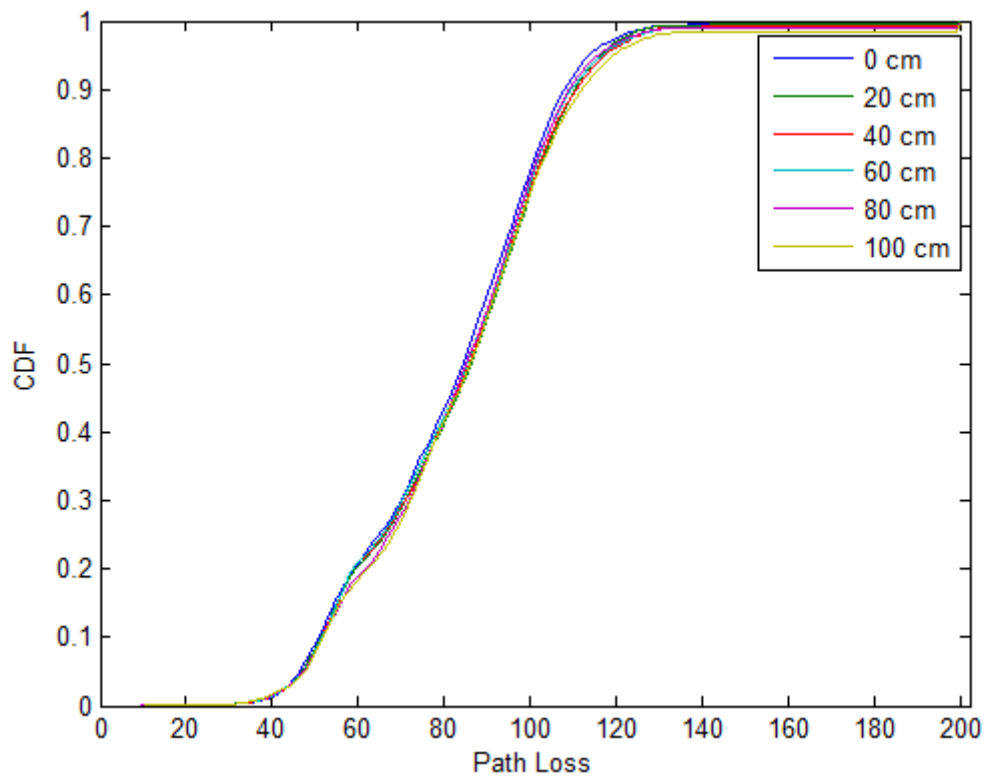


Figure 8.14: Cumulative probability distribution functions of the path loss values throughout the environment with people when the base station is at (5.675, 5.725) and when it moves westward to a maximum of 1 metre with a step of 20 centimetres

In addition, the same concept can be applied when the environment is served by multiple base stations. The base station serving the receiver that lost the service must move intending to bring the service back. For example, three base stations are positioned at (7.175, 4.225), (7.175, 13.225) and (5.675, 19.225) with -6.44 dBm minimal emitted power which represents the locations that optimise equation 5.1 based on the empty environment. Using the same base stations' locations and minimal power in both the closed environment and the environment with people and comparing the coverage, 3.52% of the receivers' locations lose the service with the biggest area being served by the base station at (7.175, 13.225). Moving this base station southward up to 1 metre with a step of 20 centimetres brings the service back to 14.93%, 17.34%, 22.13%, 29.65% and 41.47% of the receivers' positions that lost the service due to the environment change. In order to bring the service back to the rest of receivers' locations the other base stations must move. This can be clearly seen in Figure 8.15 that shows the receivers' locations that lost the service and those that got it back after moving the base station at (7.175, 13.225) by 1 metre southward.

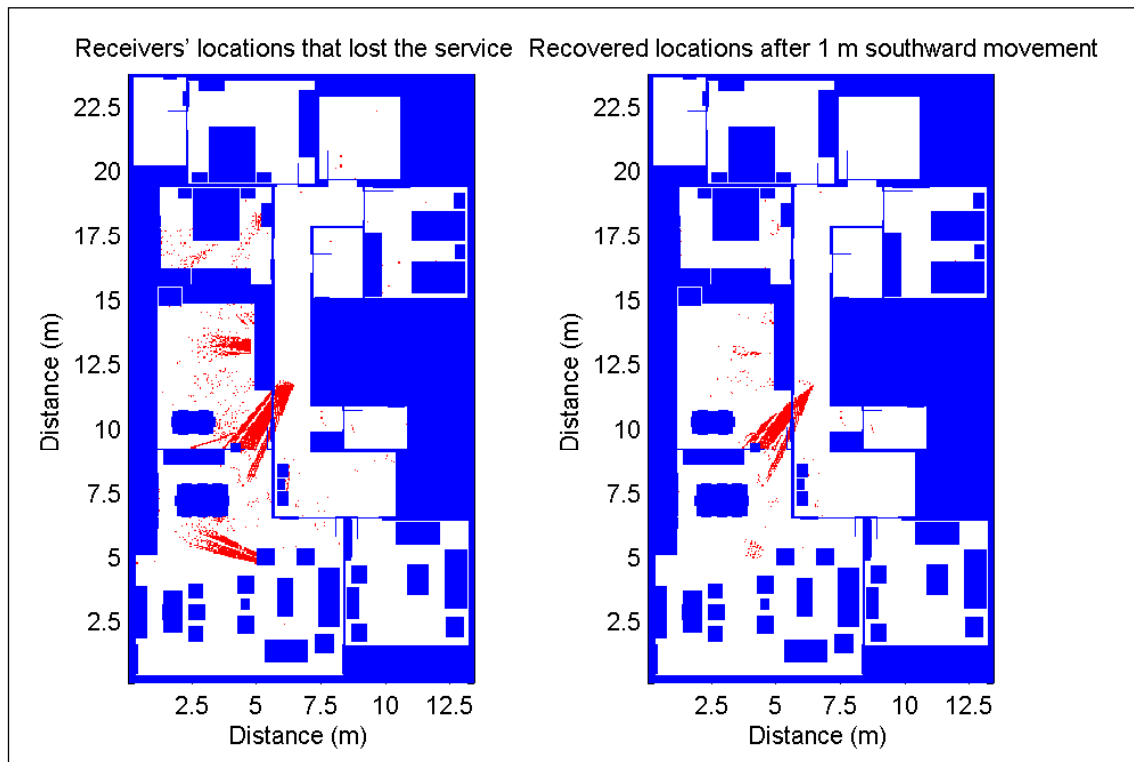


Figure 8.15: Receivers' locations that lost the service after the addition of people to the closed environment and those that got back the service after moving the base station at (7.175, 13.225) 1 metre southward while keeping the other two base stations at (7.175, 4.225) and (5.675, 19.225)

Similarly, the base station's movement technique is applied to the optimal locations obtained after the maximisation of the cost function of equation 6.1 that depends on the path loss values as well as the rms delay spread values. Unlike the polarisation change technique where if the perpendicular polarisation is used instead of the parallel polarisation, the rms delay spread values obtained for the optimal base station's location are lowered and the main controlling parameter is the path loss, the movement of the base station has a random effect on the rms delay spread distribution. In other words, the values may increase or decrease depending on the base station's location. Consequently, for low rms delay spread threshold values, both the path loss and rms delay spread values affect the percentage of receivers' locations that regains the service after losing it due to an environment change.

Starting with an example of high rms delay spread threshold, the optimal base station's position obtained in the empty environment for path loss threshold and rms delay spread thresholds of 90 dB and 400 ns respectively is (4.175, 10.225). Most receivers' locations have their rms delay spread less than the threshold and the path loss values control the coverage. Comparing the performance of the closed and open environment when the base station is placed at this location, it is noticed that 7.06% of the receivers' locations lose the service. Moving the base station in the various possible directions brings back the service to some of these receivers' locations. The best improvement is obtained if the base station is moved 1 metre eastward where 57.42% of the receivers' locations are able to enjoy the service back after the environment change.

When the rms delay threshold is lowered to 30 ns, the optimal base station's location moves to (8.675, 7.225). If the base station at this location is placed in the closed environment and then doors and windows are opened, 8.57% of the receivers' locations lose the service. Moving the base station eastward brings the service back to 55.17%, 51.85%, 51.25%, 50.96 and 50.79% of these receivers' locations. The highest improvement is 62.58% and corresponds to 80 centimetres northward movement. Note that as the base station is moving, the number of receivers' positions having their rms delay spread below 30 ns varies. This can be seen in Figure 8.16 where the receivers' locations with rms delay spread higher than 30 ns are shown in red for the original base station's location as well as when it moves 20 centimetres and 1 metre eastward. For this case, the number of receivers' locations that does not satisfy the rms delay spread threshold is increasing which if not highly affecting the percentage of recovered

receivers' locations, it will highly affect the overall coverage. The coverage percentage before moving the base station in the open environment is 60.81%. If the base station is moved 20 centimetres or 1 metre eastward, the coverage becomes 54.78% and 53.29% respectively. However, if the coverage percentage is found based on the path loss values alone, the coverage would be 58.54% and 58.09% for the 20 and 100 centimetres eastward movements respectively.

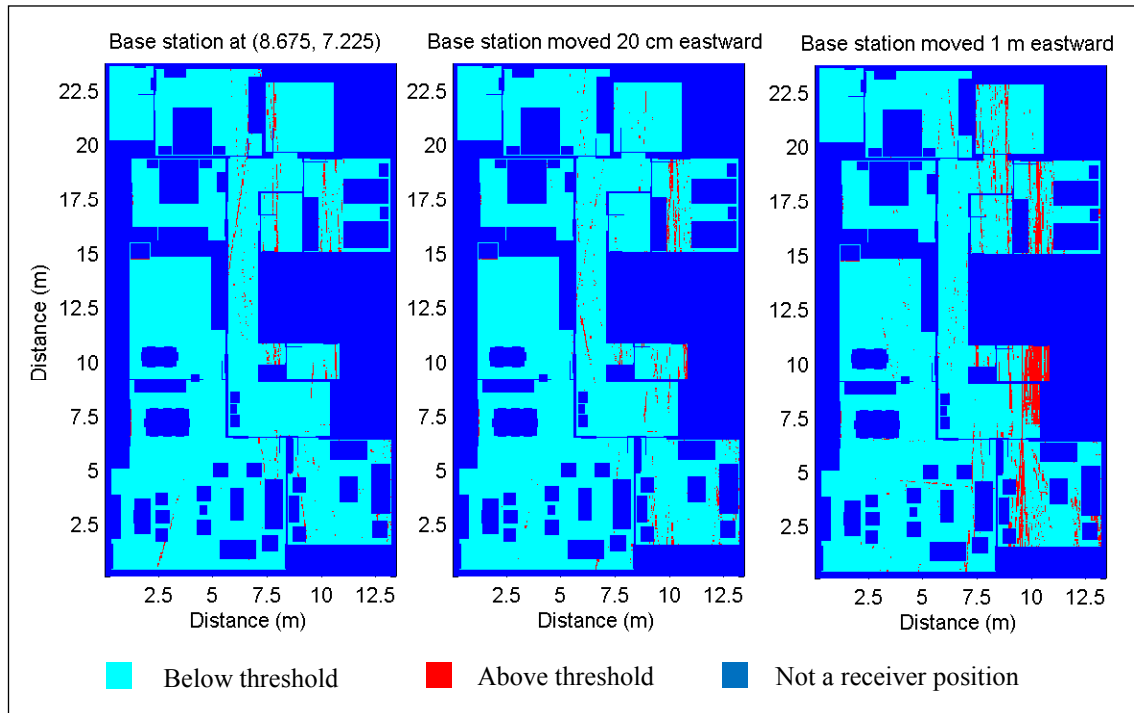


Figure 8.16: Receivers' positions having their rms delay spread below the thresholds of 30 ns for a transmitter's position coordinates of (8.675, 7.225) and when the transmitter is moved 20 centimetres and 1 metre eastward

Similar observations apply when multiple base stations serve the environment. The movement of each base station brings the service back to some of the receivers' positions that lose it due to environment changes in the area it is serving. For a high rms delay spread threshold, the percentage of those receivers' locations is controlled by path loss values only. For a low rms delay spread threshold, both the path loss and rms delay spread control the percentage of the recovered receivers' locations as the number of receivers' locations satisfying the rms delay spread varies with the base station's movement.

8.5 Conclusions

Any indoor environment is susceptible to changes such as opening doors and windows or even the presence and movement of people which will affect the service throughout the environment and some active receivers may lose the service. By monitoring the receiver's power, the base station will recognise that the user is losing the service and must react accordingly. This chapter discussed three possible techniques that may be used to overcome the effect of environment changes. In the first technique, the base station increases its emitted power until the service is back to the receiver. The drawback of this technique is that the base station's power may reach its maximum while the receiver does not get the service back in addition to the interference this may cause to neighbour base stations if high power is used.

As for the second technique, the antenna polarisation is varied so that the coverage area changes. In this way, there is a possibility that a receiver that lost the service gets it back. This technique is less effective if the path loss threshold below which a receiver's location is assumed to be served is low. For low path loss threshold, the covered area is close to the base station where the two polarisations offer similar path loss values. Regarding the overall coverage, if the path loss threshold is high, the perpendicular polarisation provides higher coverage otherwise both polarisations will result in similar coverage percentage though with a different distribution throughout the environment. Furthermore, the use of the time dispersion parameter as a second coverage criterion beside the path loss does not have any effect on the efficiency of this technique. Changing the polarisation from parallel to perpendicular lowers the rms delay spread values and the controlling parameter is the path loss. However, this can improve the overall coverage as some of the receivers' locations may initially be satisfying the path loss criterion but not that of the rms delay spread. When the rms delay spread values are lowered, some may become lower than the threshold and the corresponding receivers' locations will be served if the path loss is below the threshold too.

The third suggested technique is to provide the base station with the ability of moving automatically for a limited distance northward, southward, westward or eastward as long as there are no obstacles on the path it will follow. The distance tested in this chapter is 1 metre with a step of 20 centimetres. As the base station is moving,

different receivers' locations recover. The efficiency of this technique differs based on the direction and distance of movement. In addition to the locations of interest (the ones that lost the service due to environment changes), after the movement of the base station some receivers' locations will lose the service while other will gain service. If the path loss is the only criterion used to specify the covered locations or if both the rms delay spread and the path loss values are used as coverage criteria but with high rms delay spread threshold, the overall coverage percentage does not highly vary. This is because the cumulative probability distribution functions for the different possible base station's locations after the limited movements are close to that of the original location although this depends on the considered environment change. The cumulative distribution functions are not exactly identical if people are added to the environment and they may become different if the base station is moving close to a person in this case the coverage percentage will vary. As for the rms delay spread, the changes do not overcome the threshold as it is high. Note that the rms delay spread values changes are unpredictable. They may increase or decrease depending on the location of the base station relative to obstacles. On the other hand, if the rms delay spread threshold is low, the overall coverage may increase or decrease in a notable manner as the number of receiver locations with rms delay spread below the threshold may vary.

The main problem of the last two techniques is that after the polarisation change or the movement of the base station to bring the service back to a certain active receiver, other active users may lose the service. In this case, a decision must be made to whether the base station should go back to its original state or not.

The three techniques can be used when the environment is served by multiple base stations. The base station serving the receiver that lost the service due to an environment change is supposed to react as long as none of the other base stations is able to handle the service. Note that when multiple base stations are used, the amount of power each base station must emit is lowered and the base station can have higher range of power increase when the first suggested technique is applied, but this may affect the coverage areas of the other base stations serving the environment and the receivers' allocation to the base stations may change.

Chapter 9: Conclusions and Future Work

9.1 Conclusions from Main Research Investigation

The performance of wireless communication systems depends on the channel characteristics that vary mainly with the base station's location as well as its corresponding parameters such as the frequency, antenna polarisation and radiation pattern as well as the emitted power. The optimal base station's location must then be found to reach the highest system performance. This initially requires knowledge of the channel characteristics. Various channel modelling techniques exist and are classified as empirical or deterministic. Empirical models are simple to implement at the cost of low accuracy. On the other hand, deterministic models require detailed information about the environment constituents and the corresponding material types. They produce more accurate results but with high computation time and memory requirements.

This work focuses on dynamic indoor environments where the channel characteristics depend on individual environments, consequently a deterministic model is needed. A sophisticated 2D ray tracing program previously developed at the University of Bath [3][4] has been selected. The software requires the 2D map of the environment produced using the corresponding drawing tool based on equal dimension rectangular cells in addition to the permittivity and conductivity of the materials available in the environment. Rays are launched and tracked as they propagate through the environment and are incident on the environment constituents. The propagation mechanisms taken into consideration are the reflection and refraction. Note that the diffraction can be ignored as shown in chapter 4. Each ray is traced until its power falls below a predefined cut-off. Lower cut-off values enhance the accuracy while increasing the simulation time.

Once the channel characteristics are known, the problem of finding the optimal base stations' locations is mathematically modelled into a cost function with the variables being the base stations' coordinates. The cost function can be formed based on different channel characteristics' parameters. The main parameter of interest is the field strength or equivalently the path loss. The first new cost function proposed in this work was presented in chapter 5. It is defined to be the summation of the path loss average and standard deviation scaled by a trade-off factor used to specify whether the average

or the standard deviation must have higher influence on the cost function values. Minimising this cost function reduces the overall path loss values through the environment and lowers the number of receivers' positions with the highest path loss. The optimal base stations' coordinates obtained when this cost function is minimised were compared with those obtained when the cost function defined in [44] is optimised and the results are shown to closely match providing higher coverage percentage.

When the environment is considered empty and higher priority is given to the standard deviation, the base station is in the centre of the environment which reduces the high path loss at both ends of the environment. Increasing the trade-off factor gives higher influence to the average path loss and the base station relocates in a way that increases the area with low path loss while a higher number of receivers' locations has the highest path loss. On the other hand, if multiple base stations serve the environment, the path loss values throughout the environment are lessened and the maximum attainable path loss value drops as the number of base stations increase. As the trade-off factor is decreased, one or more of the base stations gradually get closer to areas with the highest path loss reducing the number of receivers' locations with the worst service. As soon as the optimal base stations' positions are found, the minimal amount of power needed to provide service to a predefined percentage of the possible receivers' locations can be calculated. This can be iteratively determined where the initial power is selected to be high and then reduced as long as the calculated coverage is higher than the required coverage. The decrement is fine-tuned once the calculated coverage gets closer to the desired coverage. Note that a receiver's position is assumed to be served if its corresponding path loss is less than a predefined threshold computed based on the receiver's sensitivity. As the desired coverage percentage increases, higher power is required. Furthermore, the use of multiple base stations highly reduces the total power requirements. For example, using three base stations instead of one base station reduced the total power 100 times based on the test environment considered in chapter 5.

Based on the 2D channel modelling, adding furniture to the environment tremendously increases the path loss values, thus the power requirements in the furnished environment are greater than that in the empty environment. It was around 35 times more when three transmitters were serving the test environment. The addition of furniture does not only affect the power requirements but also the optimal base stations' locations. The first detailed analysis and quantified results of the effect of a dynamic

environment on the optimal base stations' positions and minimal emitted power were presented in chapters 5 and 7. It was shown that the optimal base stations' positions are sensitive to changes that may occur in the indoor environment such as the opening of doors and windows or the addition of people. For some cost function parameters values, the optimal base stations' locations may not vary after the environment change. If the base station is close to the location of the environment change, the change will have higher effect on the path loss values hence the probability that the base station will relocate is elevated. Note that even if the base stations do not relocate after the environment change, the minimal power required to cover a predefined percentage of the receivers' positions will change. It will increase with the presence of people in the environment as the human body attenuates the signal through absorption [63].

In addition, in a furnished environment, it is possible to specify areas where receivers are more likely to exist. To take this into account while finding the optimal base stations' locations, priority weights can be assigned to each possible receiver's location. The inclusion of priority weights in the cost function definition brings the base stations near the areas containing the most receivers' locations with high priority for low trade-off factor values. This creates high path loss zones where low priority receivers' locations exist and supplementary power will be required to keep the desired coverage percentage. Furthermore, when multiple base stations serve the environment, the receivers' allocation into the base stations may be unbalanced as the base stations may get close to each other. As the trade-off factor is increased, the base stations progressively move away from high priority areas and may reach centre locations if the priority weights distribution is not highly condensed.

As the optimal base stations coordinates vary with the selection of the trade-off factor, one would ask what is the recommended value. Actually, this depends on the path loss threshold and whether priority weights are assigned to the possible receivers' locations or not. A trade-off factor less than 0.5 is recommended when no priority weights are used with a high path loss threshold as this lead to higher coverage. If the path loss threshold is low, a trade-off factor greater than 0.5 lead to higher coverage. Recall that the path loss threshold is selected based on the receiver's sensitivity. However, when priority weights are assigned to the receivers' locations, the recommended trade-off value depends on what one needs to achieve in terms of covered locations. Higher overall coverage is attained for trade-off values above 0.5 but a lower

percentage is where high priority weights receivers exist. The reverse happens when the trade-off factor is less than 0.5

The optimal base stations' locations and minimal emitted power were always found based on empty environments. However, based on the results shown in chapters 5 and 7, it is better if these are found based on the furnished environment though it is sometimes not possible as the base stations' positions may be selected in the design stage.

On the other hand, a receiver's position getting enough field strength does not necessarily mean it will enjoy the service as this depends on the time dispersion parameters. If the rms delay spread gets larger than the symbol rate, inter-symbol interference occurs [1] and the service deteriorates. As the rms delay spread value increases beyond the symbol rate, the bit error rate increases and the service worsens. Consequently, the time dispersion parameters cannot be ignored while finding the optimal base stations' locations as it has always been in the literature, especially when indoor wireless systems are evolving and greater symbol rates are achieved. Three novel cost functions were presented in chapter 6 accordingly. The cost functions take into consideration both the path loss and rms delay spread values, for the first time in the literature. The first cost function form maximises the number of receivers' positions that have their path loss and rms delay spread less than predefined thresholds where the thresholds are specified based on the receiver's sensitivity and the symbol rate. The second cost function maximises the number of receivers' positions having their path loss less than the threshold while giving higher priority to these having both the path loss and rms delay spread less than the thresholds. For most cases considered in this work, both functions ended up with the same optimal base stations' locations. When they lead to different optimal positions, the optimal positions obtained based on the latter equation provide less guaranteed service area but higher overall coverage including guaranteed and uncertain service, with the uncertain service being in the regions where the receiver satisfies the path loss criterion only. If the rms delay spread values in the uncertain coverage region are not far from the threshold, receivers within that region will have limited service. However, if the rms delay spread values are far from the threshold, the receivers will not enjoy the service. In this case, it would be better to place the base stations based on the maximisation of the first equation and get higher guaranteed service area. The choice of one of these two cost functions depends

on how high the rms delay spread values are compared to the threshold. This depends on the form and constituent of the environment. The third cost function treats the receivers' positions having the path loss less than the corresponding threshold and those having the rms delay spread less than the threshold independently. A trade-off factor is used in this case to specify which parameter must have higher influence on the cost function values. For the latter cost function to lead to optimal base stations' positions that provide satisfactory coverage, higher importance must be given to the path loss values thus the trade-off factor must be chosen higher than 0.5. This is due to the fact that a receiver's position with low rms delay spread and high path loss compared to the thresholds does not enjoy the service. The 0.7 trade-off factor led to the same optimal positions of either one of the two other cost functions. It is therefore a reasonable value to take the time dispersion parameter into consideration without making the path loss values dominate.

It was verified that the inclusion of the time dispersion parameter to the cost function affects the optimal base stations' positions. In other words, the maximisation of the cost when only the path loss values are considered and when both the path loss and rms delay spread values are used leads to different optimal base stations' locations. Therefore, the time dispersion parameter should not be ignored especially with higher data rate systems. For low speed systems, the time dispersion parameter does not highly affect the optimal base stations' positions and the main controlling parameter in the optimisation process is the path loss although this is dependent on the form and constituent of the environment. The maximum data rate below which the time dispersion parameter can be ignored is therefore environment dependent. It was shown that high rms delay spread values are obtained in the environment's corridor thus, in a narrow environment, the rms delay spread are expected to be high. Similarly, if the environment contains metallic objects, high rms delay spread values are anticipated due to the total reflection that occurs when the signal hits a metal which extend the life time of the signal and lead to more reflections. For high data rate systems (low rms delay threshold), the optimal base stations' locations are shifted away from the centre toward the sides of the environment. This reduces the number of reflections the ray undergoes as it has to travel longer distance which weakens its strength before being reflected. Furthermore, when the path loss threshold is reduced, the base stations move toward wide areas with least obstacles which increases the number of receivers' locations

having low path loss values that will mainly be in the area around the base station. Concerning the coverage, it drops as the path loss or rms delay spread thresholds are decreased. In this case, a single base station cannot handle the environment alone and additional base stations are necessary.

The optimal base stations' positions obtained after maximising the cost function based on the path loss and rms delay spread values are also affected by the addition of furniture to the environment. The presence of furniture can lower the rms delay spread values compared to the empty environment as the signal will face more objects and depending on the corresponding material type it can be highly attenuated and reflected back sooner. The optimal base stations' positions may also vary after changes that can regularly occur in any indoor environment such as opening doors and windows as well as the presence of people.

On the other hand, environment changes can prevent an active receiver from getting the service. Some intelligence must then be added to the base stations so that they can detect changes occurring in the environment mainly by monitoring the receivers' power. As soon as the base station detects environment changes, it must act accordingly in order to bring the service back to the active receiver. Three techniques were suggested. The first technique allows the base station to increase its power until the receiver regains the service. It is possible that the base station increases its power to the maximum it can achieve and the receiver does not regain the service. In the second method the antenna polarisation is varied. Changing the polarisation leads to different signal distribution that may result in different covered locations. The efficiency of the polarisation change technique to overcome the effect of environment changes depends on the path loss threshold below which a receiver's location is assumed to be served. If this threshold is low, the two polarisations offer almost the same coverage area which is around the base station. In this case, the polarisation change is not efficient. However, as the path loss threshold gets higher, the technique becomes more efficient and the perpendicular polarisation offers higher coverage area. In terms of rms delay spread, the perpendicular polarisation reduced those values when the base station is at its optimal position. The rms delay spread does not affect the efficiency of the polarisation change technique though it can increase the coverage when the perpendicular polarisation is used instead of the parallel polarisation as some of the receivers' locations may initially be satisfying the path loss criterion but not that of the rms delay spread. As the rms

delay spread values are lowered, the number of receivers' locations satisfying both criteria may increase.

The third technique gives the base station the ability to automatically move for a limited distance northward, southward, westward or eastward as long as there are no obstacles on the path it will follow. Chapter 8 presented the first published use of base station's movement as a solution to reduce the effect of a dynamic environment on the service. As the base station is moving, different receivers' locations recover. The efficiency of this technique changes with the direction and distance of movement. When the base station is displaced, some receivers' locations will lose the service while others will be served. The overall coverage percentage is not highly affected when the path loss criterion is used alone to specify the covered locations or when both the path loss and rms delay spread are used but with high rms delay spread threshold. This is because the path loss cumulative probability distribution functions for the different possible base station's locations after the limited movements are close to that of the original location unless people are added to the environment and the base station is moving close to a person where the coverage percentage will vary. As for the rms delay spread values, they change randomly (they may increase or decrease) but they do not bypass the threshold when it is high whereas, if the threshold is low, the coverage percentage may increase or decrease in a notable manner depending on the rms delay spread values variation with respect to the threshold. The main problem of the last two techniques is that once the polarisation of the base station is changed or the base station moves to bring the service back to a certain active receiver, other active receivers may lose the service. In this case, the base station must decide whether it should go back to its original state or not based on the priority of the data being transferred for example. This requires change in the standard base station operation.

The three techniques can be applied when multiple base stations are serving the environment where the base station operating the receiver that lost the service due to the environment change takes action if none of the other base stations is able to handle the service instead.

9.2 Future work

Throughout this work, a brute force optimisation approach was used as the cost function was defined over a limited discrete set of base stations' coordinates. However, as the set of base stations' coordinates grows, the brute force optimisation becomes time consuming especially when multiple base stations are assumed to serve the environment, which would make its use impractical. Genetic algorithm was tested and resulted in different optimal base stations coordinates from trial to trial, thus the first thing to be done as future work is to try other possible optimisation algorithms and find the most appropriate one.

As discussed in chapter 4, the perpendicular polarisation simulation time is at least three times more than that of the parallel polarisation and the parallel polarisation was therefore adopted. It is believed that the polarisation selection will not affect the general conclusions, although the optimal base stations' positions may change when perpendicular polarisation is used instead of parallel polarisation when the cost functions defined in chapter 7 are used with low path loss and rms delay spread thresholds as discussed in section 7.6. The optimisation process of the various cost functions defined throughout this work can then be repeated when the perpendicular polarisation is used in order to check the effect of the polarisation selection on the optimal base stations' positions.

Furthermore, when multiple base stations were serving the environment, the co-channel interference was neglected. Within the 2.4 GHz range, one can find three non-overlapping channels. The maximum number of base stations used throughout this work is three although the same frequency was used when generating the channel characteristics for each base station. The frequency deviation between these channels is small, thus the difference in channel characteristics is expected to be small and was neglected. As the number of base stations' increases, one cannot find non-overlapping channels thus the co-channel interference might be taken into consideration when defining the cost function to find the optimal base stations' positions. In addition, the cost function defined in equation 6.1 can be modified so that the receivers' locations having their path loss less than the threshold and their rms delay spread not far from the threshold are maximised along with those having both path loss and rms delay spread

below the threshold. This can be achieved by introducing a factor that decreases as the rms delay spread gets farther from its threshold.

On the other hand, the control system that allows the base station to move in different directions to reduce the effect of environment changes can be designed and implemented. One solution is to place the base station on a mini-car robot that takes movement orders from the base station once it detects the need to move after an active receiver loses the service due to environment changes. Finally, the three techniques suggested to overcome the effect of environment changes can be combined together which may improve their efficiency compared to when each of them is used independently. Furthermore, beamforming is a possible solution to bring the service back to positions that lost it. This can be tested after modifying the ray-tracing software.

Appendix A

The effect of varying the parameters of the new cost function defined in equations 5.1 and 5.2 was discussed in chapter 5. The chapter also showed the detailed analysis and quantified results of the effect of environment's changes on the optimal base stations' positions and minimal emitted power for the first time in the literature. In order to show that the observations are not environment specific, another indoor environment is considered. The environment is a $17.1 \text{ m} \times 7.8 \text{ m}$ home. The 2D map of the environment was produced using the drawing tool of the ray tracing software previously defined in chapter 4 based on $5 \text{ cm} \times 5 \text{ cm}$ cells. The resulting map is shown in Figure A.1 where each colour represents a material type. The environment consists of hollow blocks as well as concrete with some wood and glass windows, doors and furniture. It also contains a stainless steel fridge. The permittivity and conductivity values of the material present in the environment are assumed to be the same as those used with the previous environment (Table 4.1). As for the transmitter's frequency, it was tuned to 2.4 GHz and the parallel antenna polarisation was selected. Furthermore, the cut-off power level was set to -90 dB.

The environment was firstly considered empty. Furniture is then added to the environment with all doors and windows closed (denoted the closed environment). Finally, five persons were added to the environment and most doors and windows were opened (denoted the open environment with people). Note that people are shown in green in the environment's map (Figure A.1). The optimal base stations' locations were found for different trade-off factor values and different priority weights when the environment is assumed to be served by one, two or three base stations. The priority weights distribution is shown in Figure A.2. The resulting optimal base stations' Cartesian coordinates as well as the minimal emitted power required to cover 80% of the possible receivers' locations when the receiver's sensitivity is set to -65 dBm are shown in Table A.1, Table A.2 and Table A.3. It can be noticed that the base stations relocate after environment changes. The optimal base stations' locations and minimal emitted power are affected by the cost function's parameters based on the same trends discussed in chapter 5. For example, when the closed environment is served by two base stations without assigning priority weights to the possible receivers' positions, one of the base stations moves to the west side of the environment when the trade-off factor is

decreased to 0 in order to reduce the number of receivers' positions with the highest path loss (Figure A.3). Furthermore, when priority weights are assigned to the possible receivers' positions (based on Figure A.2), the two base stations gradually move away from high priority weights areas as the trade-off factor is increased (Figure A.4).

On the other hand, the addition of furniture to the environment increases the minimal amount of power required to cover a predefined percentage of the receivers' positions. As an example, when the trade-off factor is set to 0.7 and no priority weights are assigned to the possible receivers' positions, the closed environment requires 10.73 dBm whereas the empty environment requires 8.85 dBm to cover 80% of the possible receivers' positions. Opening doors and windows and adding people to the environment increase the minimal power to 13.47 dBm. In addition, for a trade-off factor of 0.7 and without assigning priority weights to the possible receivers' positions, the total power required to cover 80% of the receivers' positions when two or three base stations serve the closed environment is 27.48 times and 54.69 times less than that when one base station serves it.

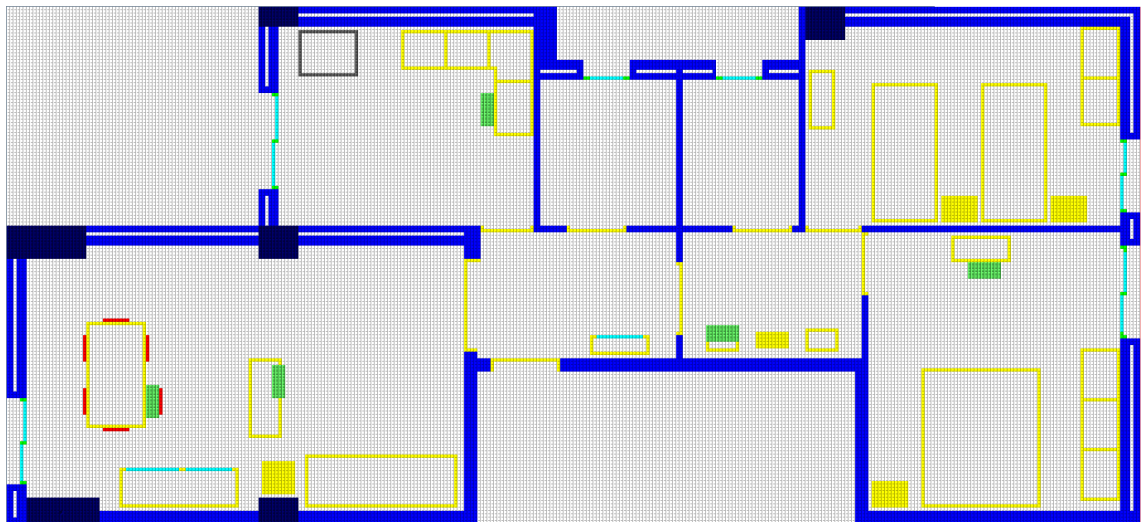


Figure A.1: Second environment 2D map as viewed in the ray tracing drawing tool

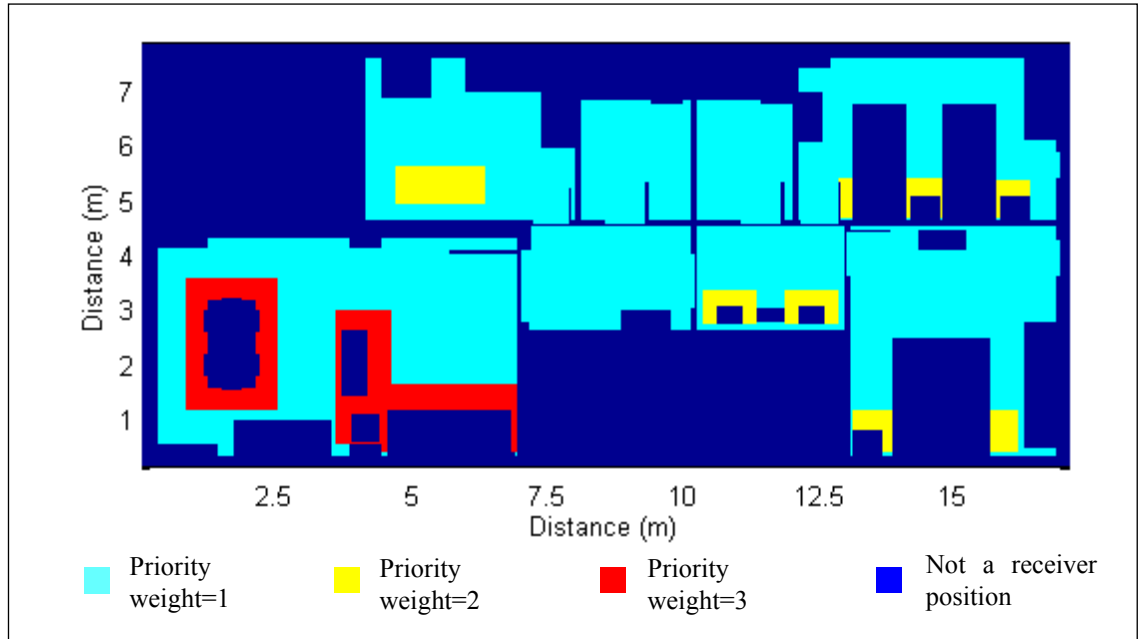


Figure A.2: Priority weights values throughout the second furnished environment

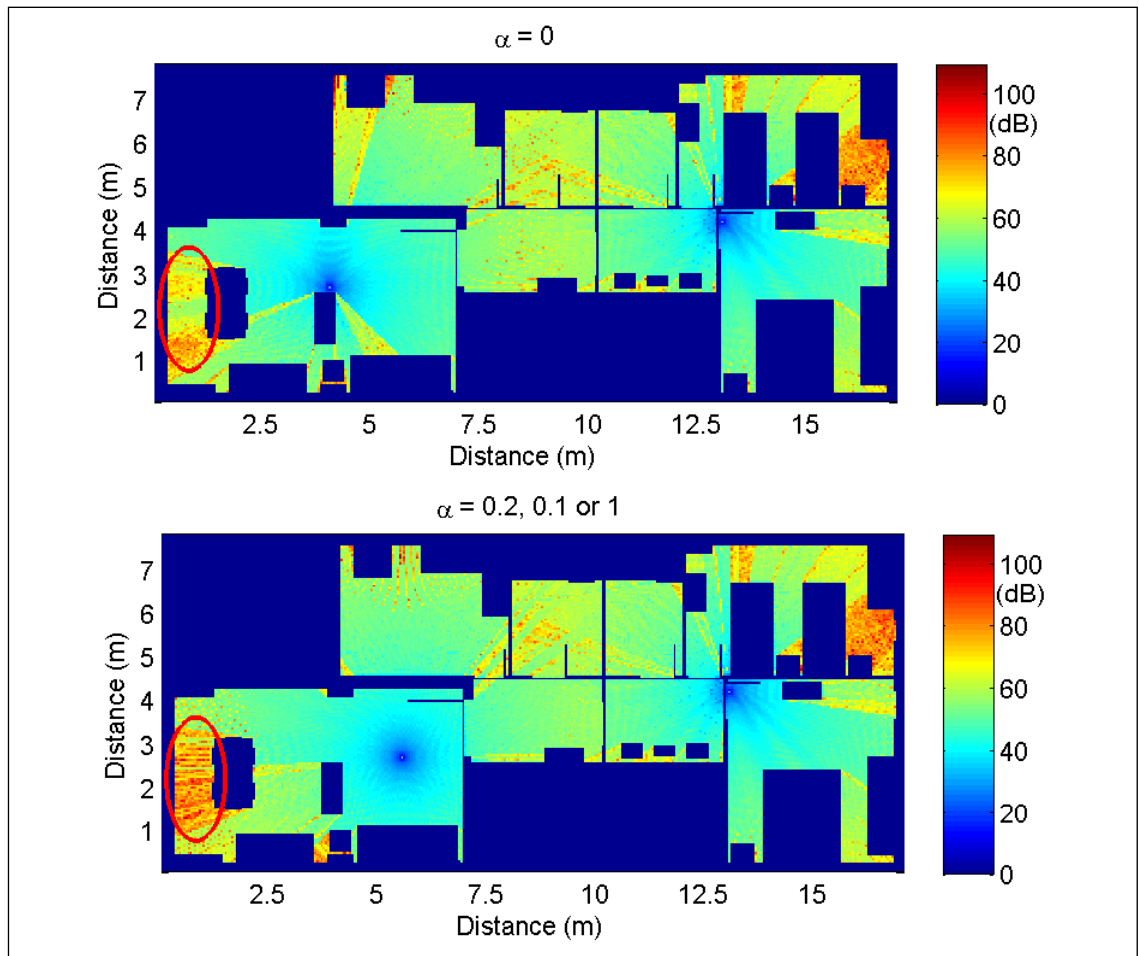


Figure A.3: Path loss in dB at the possible receivers' positions throughout the second closed environment when two transmitters are at their optimal locations for trade-off factor equals 0, 0.2, 0.7 and 1 without the use of priority weights

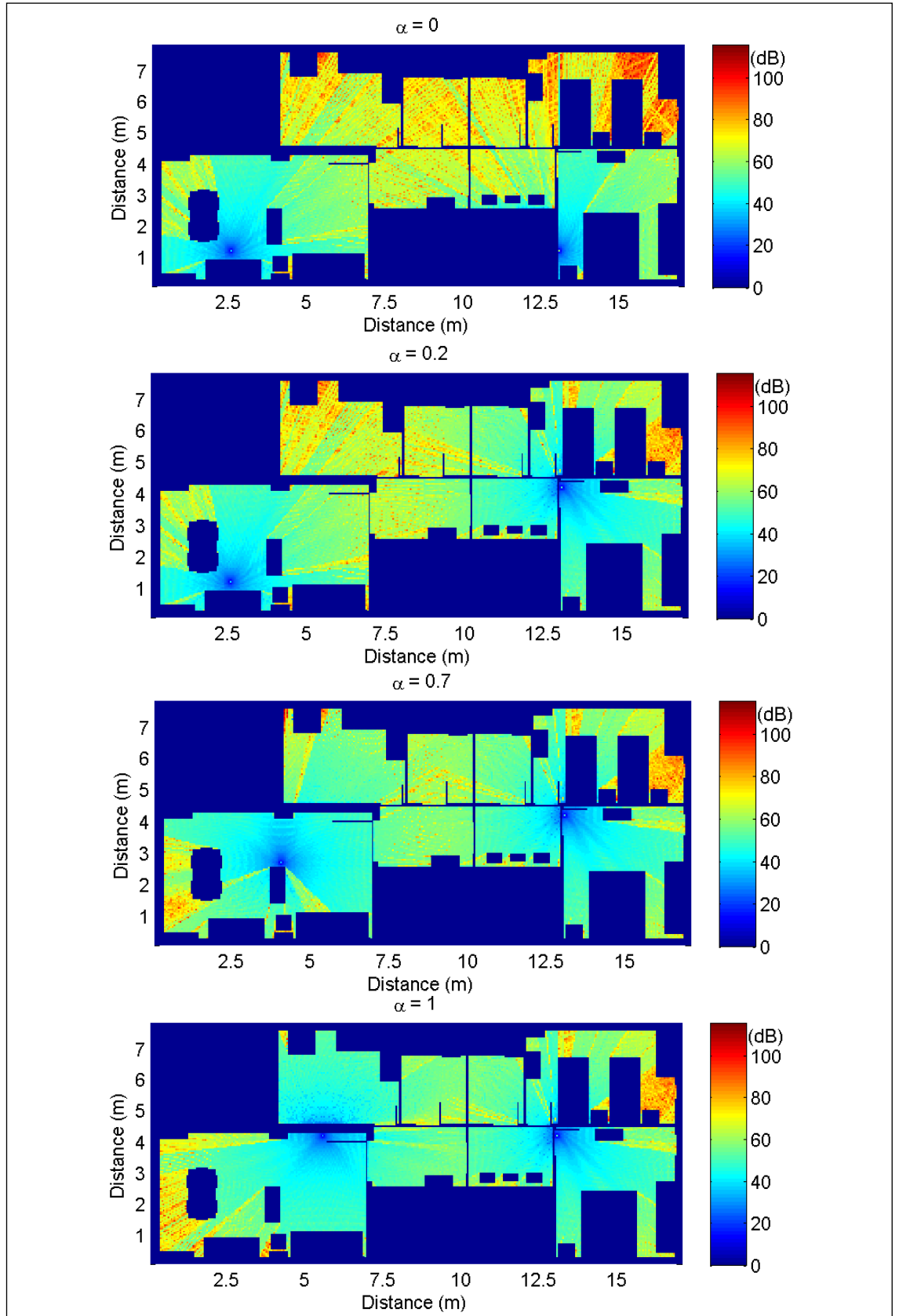


Figure A.4: Path loss in dB at the possible receivers' positions throughout the second closed environment when two transmitters are at their optimal locations for trade-off factor equals 0, 0.2, 0.7 and 1 with priority weights set to 1, 2 or 3

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(10.025, 2.625) 9.24 dBm	(10.025, 2.625) 9.24 dBm	(10.025, 4.125) 8.85 dBm	(10.025, 4.125) 8.85 dBm
	$W_i=1$	(11.525, 2.625) 24.53 dBm	(10.025, 4.125) 10.73 dBm	(10.025, 4.125) 10.73 dBm	(10.025, 4.125) 10.73 dBm
Closed Environment	$W_i=1, 2$ or 3	(2.525, 2.625) 22.29 dBm	(4.025, 2.625) 20.36 dBm	(5.525, 4.125) 14.73 dBm	(5.525, 4.125) 14.73 dBm
	$W_i=1$	(11.525, 2.625) 25.69 dBm	(10.025, 4.125) 13.47 dBm	(10.025, 4.125) 13.47 dBm	(10.025, 4.125) 13.47 dBm
Open Environment with People	$W_i=1, 2$ or 3	(4.025, 3.975) 27.54 dBm	(4.025, 2.625) 22.2 dBm	(5.525, 4.125) 20.13 dBm	(5.525, 4.125) 20.13 dBm
	$W_i=1$	(11.525, 2.625) 25.69 dBm	(10.025, 4.125) 13.47 dBm	(10.025, 4.125) 13.47 dBm	(10.025, 4.125) 13.47 dBm

Table A.1: Optimal base station's coordinates and minimal amount of emitted power required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty and closed environments as well as the open environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(5.525, 4.125) (13.025, 4.125) -11.2 dBm	(5.525, 4.125) (13.025, 4.125) -11.2 dBm	(5.525, 4.125) (13.025, 4.125) -11.2 dBm	(5.525, 4.125) (14.525, 4.125) -11.23 dBm
	$W_i=1$	(4.025, 2.625) (13.025, 4.125) -5.43 dBm	(5.525, 4.125) (13.025, 4.125) -6.67 dBm	(5.525, 4.125) (13.025, 4.125) -6.67 dBm	(5.525, 4.125) (13.025, 4.125) -6.67 dBm
Closed Environment	$W_i=1, 2$ or 3	(2.525, 1.125) (13.025, 1.125) 6.75 dBm	(2.525, 1.125) (13.025, 4.125) -0.47 dBm	(4.025, 2.625) (13.025, 4.125) -5.43 dBm	(5.525, 4.125) (13.025, 4.125) -6.67 dBm
	$W_i=1$	(4.025, 2.625) (13.025, 4.125) -3.47 dBm	(4.025, 2.625) (13.025, 4.125) -3.47 dBm	(5.525, 4.125) (13.025, 4.125) -3.37 dBm	(5.525, 4.125) (13.025, 4.125) -3.37 dBm
Open Environment with People	$W_i=1$	(4.025, 2.625) (13.025, 4.125) -3.47 dBm	(4.025, 2.625) (13.025, 4.125) -3.47 dBm	(5.525, 4.125) (13.025, 4.125) -3.37 dBm	(5.525, 4.125) (13.025, 4.125) -3.37 dBm
	$W_i=1, 2$ or 3	(5.525, 1.125) (2.525, 2.625) 13.28 dBm	(2.525, 1.125) (13.025, 4.125) 2.74 dBm	(4.025, 2.625) (13.025, 4.125) -3.47 dBm	(5.525, 4.125) (13.025, 4.125) -3.37 dBm

Table A.2: Optimal base stations' coordinates and minimal amount of emitted power per base station required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty and closed environments as well as the open environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1 (2 base stations)

		$\alpha=0$	$\alpha=0.2$	$\alpha=0.7$	$\alpha=1$
Empty Environment	$W_i=1$	(4.025, 4.125)	(4.025, 2.625)	(4.025, 2.625)	(4.025, 2.625)
		(13.025, 4.125)	(14.525, 4.125)	(14.525, 4.125)	(14.525, 4.125)
		(7.025, 5.625)	(7.025, 5.625)	(7.025, 5.625)	(7.025, 5.625)
		-12.89 dBm	-13.84 dBm	-13.84 dBm	-13.84 dBm
Closed Environment	$W_i=1$	(13.025, 1.125)	(4.025, 2.625)	(4.025, 2.625)	(14.525, 2.625)
		(4.025, 2.625)	(11.525, 4.125)	(13.025, 4.125)	(5.525, 4.125)
		(13.025, 5.625)	(14.525, 5.625)	(7.025, 5.625)	(10.025, 4.125)
		-7.1 dBm	-8.9 dBm	-9.66 dBm	-8.85 dBm
Open Environment with People	$W_i=1, 2$ or 3	(5.525, 1.125)	(1.025, 1.125)	(1.025, 1.125)	(2.525, 1.125)
		(2.525, 2.625)	(5.525, 2.625)	(5.525, 4.125)	(5.525, 4.125)
		(13.025, 4.125)	(13.025, 4.125)	(13.025, 4.125)	(13.025, 4.125)
		-5.95 dBm	-8.08 dBm	-8.86 dBm	-8.61 dBm
Open Environment with People	$W_i=1$	(13.025, 1.125)	(4.025, 2.625)	(4.025, 2.625)	(4.025, 2.625)
		(4.025, 2.625)	(14.525, 2.625)	(16.025, 2.625)	(16.025, 2.625)
		(13.025, 5.625)	(13.025, 5.625)	(10.025, 4.125)	(10.025, 4.125)
		-6.35 dBm	-7.77 dBm	-7.39 dBm	-7.39 dBm
Open Environment with People	$W_i=1, 2$ or 3	(5.525, 1.125)	(5.525, 1.125)	(1.025, 1.125)	(1.025, 1.125)
		(2.525, 2.625)	(2.525, 2.625)	(5.525, 4.125)	(5.525, 4.125)
		(13.025, 4.125)	(13.025, 4.125)	(13.025, 4.125)	(13.025, 4.125)
		-4.93 dBm	-4.93 dBm	-7.37 dBm	-7.37 dBm

Table A.3: Optimal base stations' coordinates and minimal amount of emitted power per base station required to provide 80% coverage, based on -65 dBm receiver's sensitivity, in the empty and closed environments as well as the open environment with people for different priority weights and trade-off factor values of 0, 0.2, 0.7 and 1 (3 base stations)

Appendix B

Chapters 6 and 7 discussed the effect of varying the parameters of the novel cost functions of equations 6.1, 6.3 and 6.5 that take into consideration the path loss and the rms delay spread on the optimal base stations' positions and coverage percentage. They also showed that the optimal base stations' positions are sensitive to the environment's dynamics. The same cost functions are maximised when the environment defined in Appendix A in its various forms (the empty environment, the closed environment as well as the open environment with the presence of people) is served by one, two or three base stations for different path loss and rms delay spread thresholds. The resulting optimal base stations' coordinates are shown in the following nine tables with each table corresponding to the results of one of the three cost functions.

The same observations discussed in chapters 6 and 7 are valid for the second environment. For example, looking into the optimal base station's coordinates when the empty environment is served by one base station, it can be seen that when the path loss and rms delay spread are high, the base station is in the centre of the environment. When the rms delay spread threshold is lowered to 30 ns, the base station moves to the northern border of the environment so that the rms delay spread values are lowered. Furthermore, when the path loss threshold is decreased to 50 dB, the base station moves to a wide area with least obstacles. This is illustrated in Figure B.1 that shows the path loss values at the possible receivers' positions throughout the empty environment when the base station is at the optimal positions obtained when the cost function of equation 6.1 is maximised with path loss and rms delay spread thresholds equal to 90 dB and 400 ns, 90 dB and 30 ns as well as 50 dB and 400 ns.

On the other hand, when changes occur in the environment, the base stations may relocate depending on how much the field strength and rms delay spread distributions have changed with respect to the corresponding threshold values. As an example, maximising the cost function of equation 6.1 based on the closed environment with path loss and rms delay spread thresholds of 90 dB and 400 ns when two base stations serve the environment leads to the coordinates (5.525, 4.125) and (14.525, 2.625). If the base stations are kept at these locations in the open environment with people, the coverage will be lowered. Figure B.2 shows the path loss values at the possible receivers' locations in the closed environment and the open environment with

people when the two base stations are at (5.525, 4.125) and (14.525, 2.625) with the open door and people highly affecting the path loss values circle in red and black respectively. The base stations located at (4.025, 2.625) and (13.025, 4.125) are able to maximise the cost function and provide better service within the open environment with people. The corresponding path loss distribution is shown in Figure B.3.

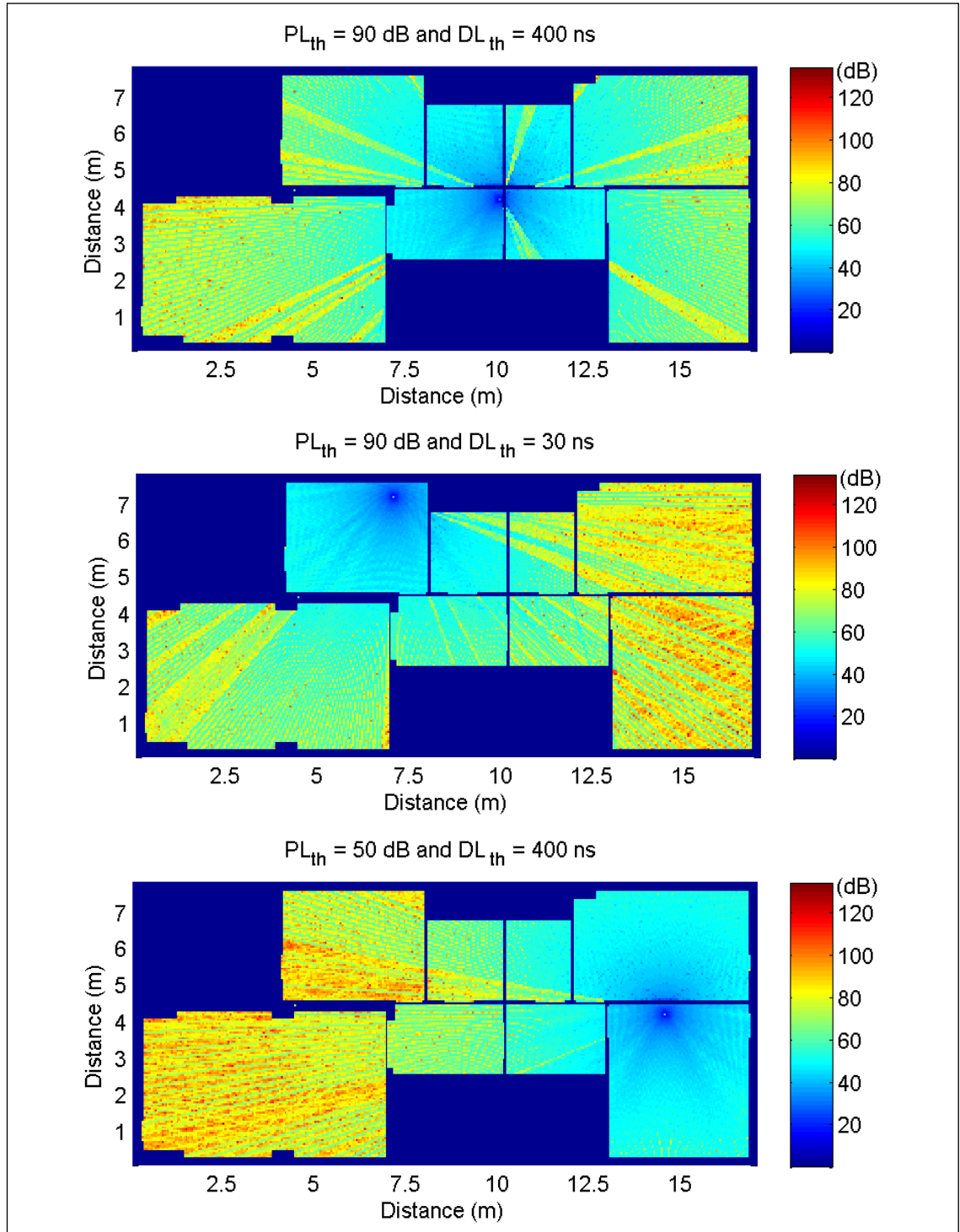


Figure B.1: Path loss in dB at the possible receivers' positions throughout the second empty environment when the transmitter is at its optimal locations obtained after maximising equation 6.1 with path loss and rms delay spread thresholds of 90 dB and 400 ns, 90 dB and 30 ns as well as 50 dB and 400 ns

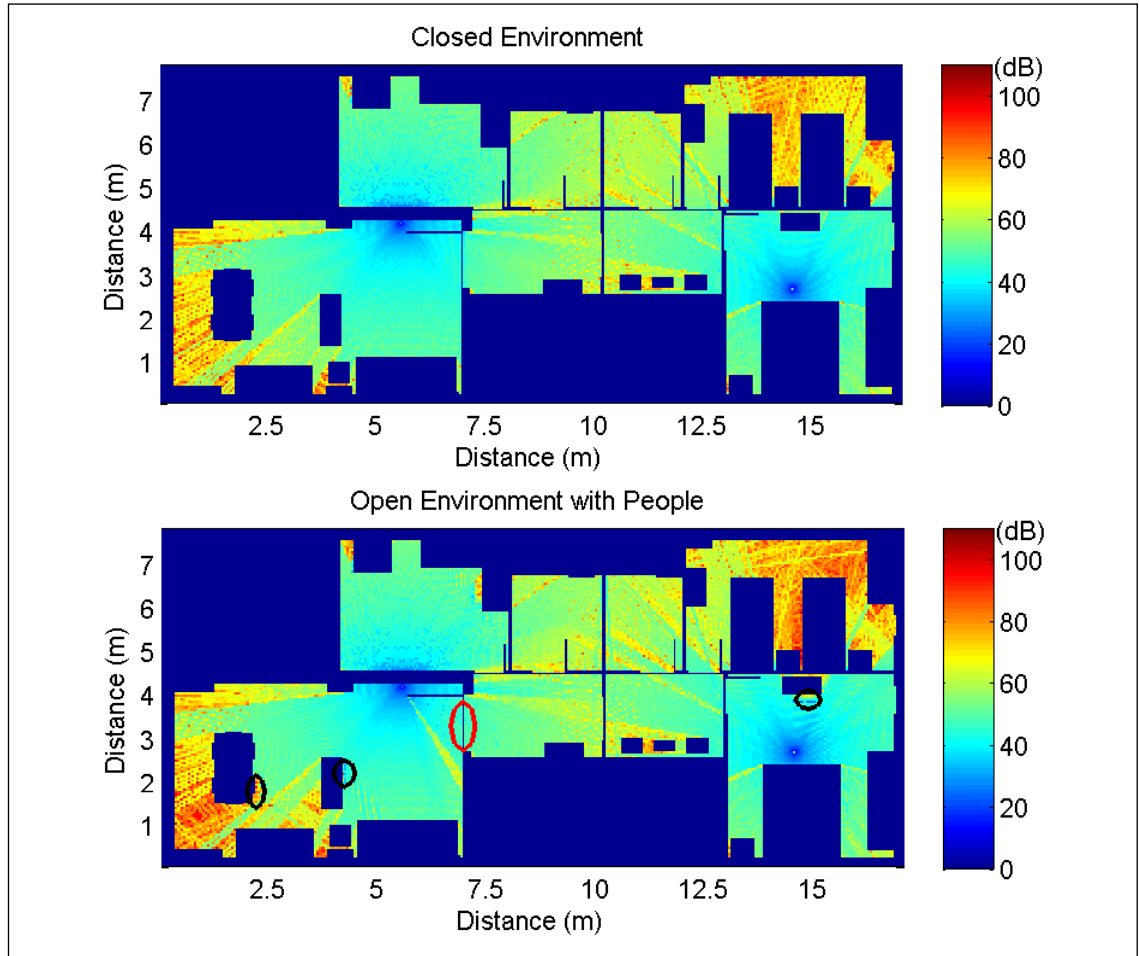


Figure B.2: Path loss in dB at the possible receivers' positions throughout the closed environment and the open environment with people when two base stations are at (5.525, 4.125) and (14.525, 2.625)

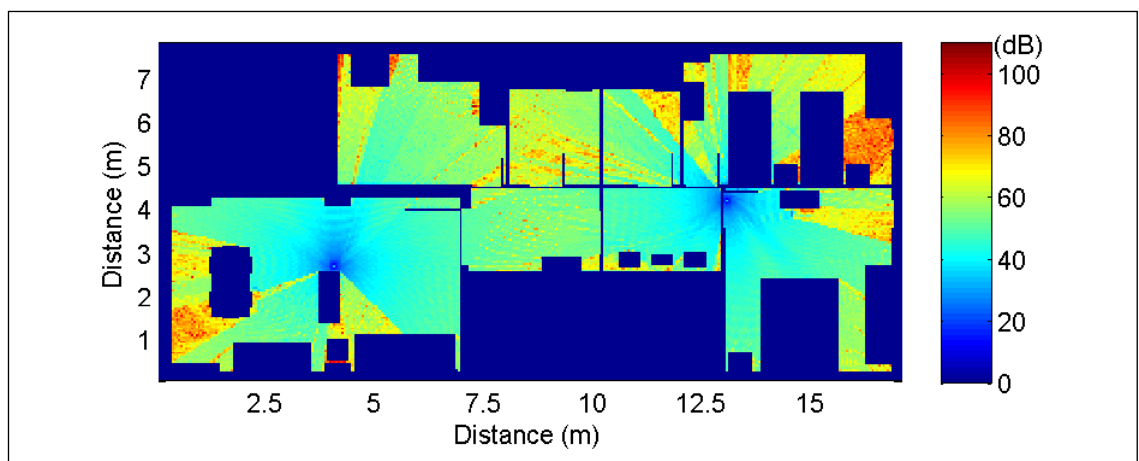


Figure B.3: Path loss in dB at the possible receivers' positions throughout the open environment with people when two base stations are at (4.025, 2.625) and (13.025, 4.125)

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(7.025, 7.125)	(10.025, 4.125)	(10.025, 2.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)

Table B.1: Optimal base station's positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.1 for different parameters' values

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(8.525, 2.625)	(10.025, 4.125)	(10.025, 2.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)

Table B.2: Optimal base station's positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.3 for different parameters' values

		Empty Environment	Closed Environment	Open Environment with people
PL_{th}=90 dB DL_{th}=400 ns	$\alpha=0$	Any position	Any position	Any position
	$\alpha=0.2$	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
	$\alpha=0.7$	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
	$\alpha=1$	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
PL_{th}=90 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125)	(16.025, 5.625)	(16.025, 5.625)
	$\alpha=0.2$	(7.025, 7.125)	(10.025, 2.625)	(7.025, 5.625)
	$\alpha=0.7$	(8.525, 2.625)	(10.025, 4.125)	(10.025, 2.625)
	$\alpha=1$	(10.025, 4.125)	(10.025, 4.125)	(10.025, 4.125)
PL_{th}=50 dB DL_{th}=400 ns	$\alpha=0$	Any position	Any position	Any position
	$\alpha=0.2$	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
	$\alpha=0.7$	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
	$\alpha=1$	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
PL_{th}=50 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125)	(16.025, 5.625)	(16.025, 5.625)
	$\alpha=0.2$	(7.025, 7.125)	(10.025, 4.125)	(7.025, 5.625)
	$\alpha=0.7$	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)
	$\alpha=1$	(14.525, 4.125)	(5.525, 4.125)	(5.525, 4.125)

Table B.3: Optimal base station's positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.5 for different parameters' values

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (14.525, 2.625)	(4.025, 2.625) (13.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(7.025, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625)	(4.125, 5.625) (13.025, 2.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(5.525, 4.125) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)

Table B.4: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.1 for different parameters' values (2 base stations)

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (14.525, 2.625)	(4.025, 2.625) (13.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(7.025, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625)	(2.525, 2.625) (13.025, 5.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(5.525, 4.125) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)

Table B.5: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.3 for different parameters' values (2 base stations)

		Empty Environment	Closed Environment	Open Environment with people
PL_{th}=90 dB DL_{th}=400 ns	$\alpha=0$	Any 2 positions	Any 2 positions	Any 2 positions
	$\alpha=0.2$	(4.025, 2.625) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125)	(4.025, 2.625) (13.025, 4.125)
	$\alpha=0.7$	(4.025, 2.625) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125)	(4.025, 2.625) (13.025, 4.125)
	$\alpha=1$	(4.025, 2.625) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125)	(4.025, 2.625) (13.025, 4.125)
PL_{th}=90 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125) (16.025, 7.125)	(1.025, 2.625) (13.025, 5.625)	(14.525, 5.625) (16.025, 5.625)
	$\alpha=0.2$	(7.025, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625)	(5.525, 5.625) (13.025, 2.625)
	$\alpha=0.7$	(7.025, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625)	(2.525, 2.625) (13.025, 5.625)
	$\alpha=1$	(4.025, 2.625) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125)	(4.025, 2.625) (13.025, 4.125)
PL_{th}=50 dB DL_{th}=400 ns	$\alpha=0$	Any 2 positions	Any 2 positions	Any 2 positions
	$\alpha=0.2$	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
	$\alpha=0.7$	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
	$\alpha=1$	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
PL_{th}=50 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125) (16.025, 7.125)	(1.025, 2.625) (13.025, 5.625)	(14.525, 5.625) (16.025, 5.625)
	$\alpha=0.2$	(7.025, 7.125) (16.025, 4.125)	(5.525, 4.125) (10.025, 4.125)	(7.025, 5.625) (13.025, 2.625)
	$\alpha=0.7$	(5.525, 4.125) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)
	$\alpha=1$	(4.025, 2.625) (14.525, 4.125)	(5.525, 4.125) (10.025, 4.125)	(5.525, 4.125) (10.025, 4.125)

Table B.6: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.5 for different parameters' values (2 base stations)

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(7.025, 7.125) (14.525, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625) (13.025, 5.625)	(1.025, 2.625) (13.025, 2.625) (7.025, 5.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(5.525, 4.125) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)

Table B.7: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.1 for different parameters' values (3 base stations)

	Empty Environment	Closed Environment	Open environment with people
$PL_{th}=90$ dB $DL_{th}=400$ ns	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
$PL_{th}=90$ dB $DL_{th}=30$ ns	(7.025, 7.125) (14.525, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625) (13.025, 5.625)	(1.025, 2.625) (16.025, 4.125) (7.025, 5.625)
$PL_{th}=50$ dB $DL_{th}=400$ ns	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
$PL_{th}=50$ dB $DL_{th}=30$ ns	(5.525, 4.125) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)

Table B.8: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.3 for different parameters' values (3 base stations)

		Empty Environment	Closed Environment	Open Environment with people
PL_{th}=90 dB DL_{th}=400 ns	$\alpha=0$	Any 3 positions	Any 3 positions	Any 3 positions
	$\alpha=0.2$	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
	$\alpha=0.7$	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
	$\alpha=1$	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
PL_{th}=90 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125) (14.525, 7.125) (16.025, 7.125)	(11.525, 2.625) (13.025, 2.625) (14.525, 5.625)	(14.525, 5.625) (16.025, 5.625) (16.025, 7.125)
	$\alpha=0.2$	(7.025, 7.125) (14.525, 7.125) (16.025, 7.125)	(1.025, 2.625) (10.025, 2.625) (13.025, 5.625)	(1.025, 2.625) (5.525, 5.625) (13.025, 5.625)
	$\alpha=0.7$	(5.525, 7.125) (7.025, 7.125) (16.025, 7.125)	(2.525, 2.625) (14.525, 2.625) (13.025, 5.625)	(1.025, 2.625) (16.025, 4.125) (7.025, 5.625)
	$\alpha=1$	(1.025, 1.125) (2.525, 1.125) (13.025, 5.625)	(4.025, 2.625) (16.025, 4.125) (7.025, 5.625)	(2.525, 1.125) (16.025, 2.625) (10.025, 4.125)
PL_{th}=50 dB DL_{th}=400 ns	$\alpha=0$	Any 3 positions	Any 3 positions	Any 3 positions
	$\alpha=0.2$	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
	$\alpha=0.7$	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
	$\alpha=1$	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
PL_{th}=50 dB DL_{th}=30 ns	$\alpha=0$	(7.025, 7.125) (14.525, 7.125) (16.025, 7.125)	(11.525, 2.625) (13.025, 2.625) (14.525, 5.625)	(14.525, 5.625) (16.025, 5.625) (16.025, 7.125)
	$\alpha=0.2$	(11.525, 4.125) (16.025, 4.125) (7.025, 7.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(4.025, 2.625) (13.025, 2.625) (7.025, 5.625)
	$\alpha=0.7$	(5.525, 4.125) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)
	$\alpha=1$	(4.025, 2.625) (10.025, 4.125) (14.525, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)	(14.525, 2.625) (5.525, 4.125) (10.025, 4.125)

Table B.9: Optimal base stations' positions in the second empty and closed environments as well as the open environment with people using the cost function of equation 6.5 for different parameters' values (3 base stations)

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